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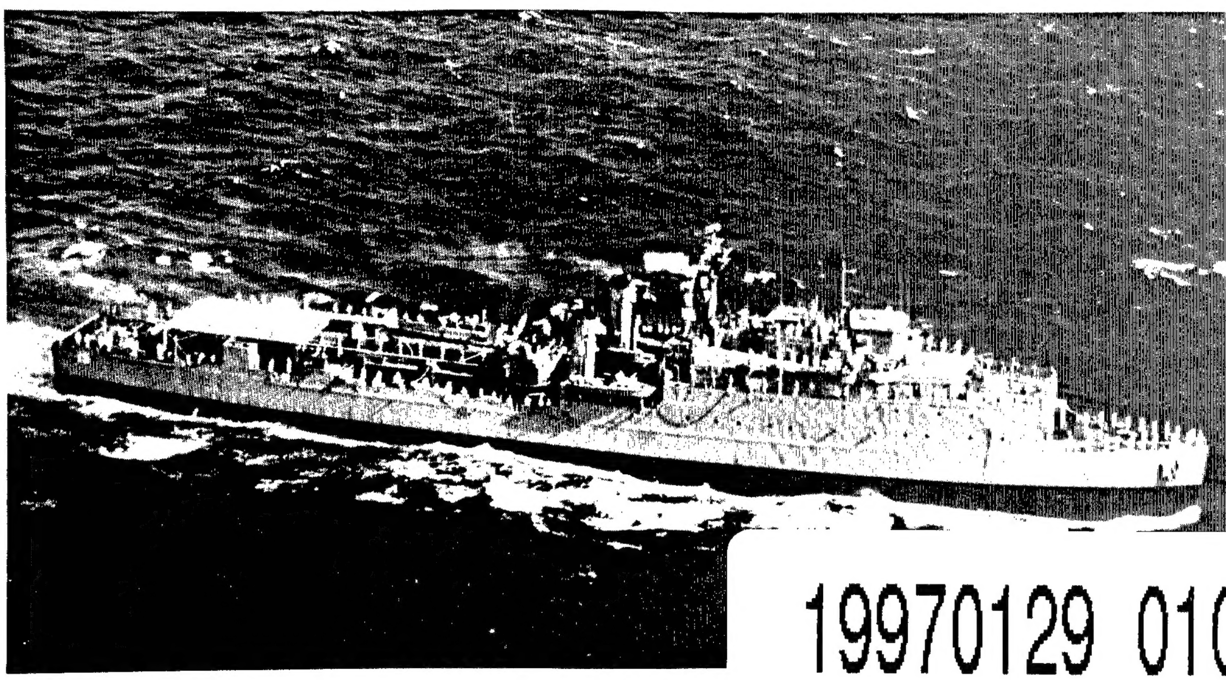
1995 Class B Firefighting Doctrine and Tactics: Final Report

F.W. WILLIAMS
J.P. FARLEY
M.J. PEATROSS

Navy Technology for Safety and Survivability
Chemistry Division

D.T. GOTTUK

Hughes Associates, Inc.
Baltimore, MD



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F.W. Williams, J.P. Farley, D.T. Gottuk,* and M.J. Peatross

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These tests show development and mitigation of Class B explosions aboard Naval ships. This consisted of three main points: 1) determining the conditions needed for developing a Class B explosion, 2) determining the effect of ship board conditions (e.g. buffer zone size and ventilation) on the development of Class B explosions, and 3) determining the effectiveness of using water spray as a mitigating tactic. Results that address all three points are discussed in detail.

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1.0 INTRODUCTION

The use of Class B fuels aboard Naval ships presents unique challenges when leaks and/or fires develop. As opposed to Class A materials, Class B fuels tend to volatilize more quickly resulting in either rapidly growing fires or the build up of fuel vapors within the space. The buildup of sufficient vapors within the space can lead to one of two potentially explosive conditions. The two explosive conditions are differentiated based on the oxygen concentration within the space. For example, a fuel leak may occur in which the fuel is either finely atomized due to a small break in a fuel line or the fuel is sprayed unto a hot machinery surface which causes the fuel to vaporize. In either case, fuel vapor/aerosol fills the space under conditions of near ambient oxygen concentrations. As the increasing fuel-to-air mixture reaches or exceeds the lower explosive limit (LEL), an ignition source is all that is required to cause an explosion. The second explosive condition occurs when there is insufficient oxygen within the space for combustion of the fuel. This scenario is likely to occur as a fire space is secured and the fire is extinguished. Residual fuel or an unsecured fuel source can continue to produce a fuel-rich environment within the vitiated space. However, without sufficient oxygen the fuel cannot burn. The potential hazard arises when the space is reentered. Breaches to the fire boundary can cause air to flow into the fire space, thus creating a combustible mixture and an explosion (i.e., backdraft). A detailed discussion of the development of hazardous conditions aboard Naval ships is included in reference (1)).

Although Class B explosions are not frequent events, reports indicate that they do occur with substantial damage to the ship and, of more importance, deadly consequences for sailors. The fatal incidents onboard the USS BENNINGTON and USS MIDWAY are examples of such explosions that have occurred on Naval ships (reference (2)). Anecdotal reports indicate that the frequency of Class B explosions may even be higher than recorded due to the lack of circulation of written accounts or full documentation of events. Regardless of the actual frequency, the nature of Class B fuels to easily create dangerous reflashes and explosions, particularly during reentry procedures, warrants study. This is particularly true since current Navy doctrine lacks specific details with regards to reentry and overhaul procedures.

1.1 Current Navy Doctrine

The Navy firefighting doctrine for machinery space Class B fires in surface ships is presented in NSTM 555 (reference (3)). The following excerpts give a summary of the key points that pertain to ventilation, boundary zones and reentry of the fire space for controllable fires. During a class B fire NSTM 555-6.3.5.5 states that "negative ventilation (exhaust on high and supply on low)" should be set in the affected machinery space while "positive ventilation (supply on high and exhaust off)" should be set in unaffected machinery spaces. "Setting positive ventilation is intended to prevent smoke on the damage control deck from entering unaffected spaces." In addition, fire and smoke boundaries are to be set around the affected space to prevent the spread of fire and smoke throughout the ship. The proceeding guidelines are for controllable fires, and therefore, fire space reentry is not an issue.

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In the case of an out-of-control fire, the space is evacuated and ventilation in the fire space and adjacent spaces is secured (Section 6.3.6). Section 6.3.7.2 states that "inner and outer smoke boundaries shall be set quickly around accesses to the affected space . . . . The area between the inner and outer smoke boundaries is designated the buffer zone and shall be a dead-air space." "The smoke boundary nearest the fire is designated as the inner smoke boundary and normally coincides with the primary fire boundary" (Section 5.3.2.6.2). The outer smoke boundary is located farther away from the fire. "These boundaries are generally the watertight bulkheads and decks immediately adjacent to the affected space (Section 6.3.8.3)." Due to the numerous existing ship designs, buffer zones can range in size from a vertical trunk to a large section of a deck. Regardless of the size, ventilation is to be secured in the buffer zone to establish a "dead-air space" (Section 6.3.7.2). "Establishing the buffer zone is important due to the possibility of fire or explosion if hot combustion gases from a Class B fire mix with fresh air. Consequently, active desmoking (paragraph 555-5.3.4C) shall not be used for machinery space Class B fires."

Firefighters are advised to reenter the space as quickly as possible, to attack and extinguish the fire and ensure the source of fuel is secured (Section 6.3.10). Guidance is given to the time at which reentry should be attempted based on the extinguishing system used and the success of the system in extinguishing the fire. However, there is little guidance with regards to the tactics to be used during the reentry procedure even though "reentry...is the most critical part of the firefighting evolution and potentially the most dangerous (6.3.10)." This lack of specific guidance was one of the motivating elements for this work. In addition, questions were raised concerning the effectiveness of establishing buffer zones as dead-air spaces as a means of preventing Class B explosions.

1.2 Series 1 Testing

The 1995 Class B Firefighting Doctrine and Tactics Test Series 1 (reference (4)) was to determine the Class B fire conditions which could lead to the venting of flammable gases to adjoining decks and compartments from a below decks Class B fire. These conditions were characterized by the fuel supply rate and the ventilation provided to the fire compartment. The ignition index criterion was examined as a possible means to monitor the explosion/reflash potential of the fire space by measuring key parameters within the fire compartment, such as temperature and fuel-to-air ratio.

The results from these small compartment tests highlight the conditions and hazards associated with Class B fires. Under burning conditions, the fires can produce high levels of toxic gases, high temperatures, and even the transport of flammable gases. However, achieving very fuel-rich burning conditions proved to be difficult. In order to sustain burning at these conditions, the air flow into the compartment had to be ducted to the base of the fire. Otherwise, the vitiated upper layer combustion gases would descend to the base of the fire causing it to be oxygen starved. It is not clear whether the phenomenon would occur in full size machinery space before surfaces become hot. As expected, this result indicates that Class B spray fires are easily extinguished under poor ventilation conditions. Several fires did self-extinguish even with the inlet duct in place. The fires that self-extinguished resulted in the formation of white mists of fuel aerosol forming outside of the fire compartment. For two of these fires, small explosions within the fire compartment occurred within a minute of the fire extinguishing. In both cases, jets of flame and/or fire balls shot out of the vents in the fire space.

For tests in which high fuel-to-air ratios were obtained, several modes of external burning were observed outside of the fire compartment. For these tests, the ignition index criterion proved to be a good prediction tool for indicating when significantly fuel-rich conditions exist such that sustained external burning can result.

The Series 1 results highlight the conditions and hazards associated with Class B fires. Of greatest concern is the susceptibility of Class B fires to extinguish and quickly create an explosive mixture. Therefore, after Series 1, goals of the program were adjusted to investigate the development of Class B explosions and possible tactics that could be used to mitigate the explosion potential of fire compartments that have been secured. This report presents the work performed in Series 2 through 5 of the 1995 Class B Firefighting Doctrine and Tactics test program.

2.0 OBJECTIVE

In general, the objective for Test Series 2 to 5 was to obtain a scientific understanding of the development and mitigation of Class B explosions aboard Naval ships. This consisted of three main points: (1) determining the conditions needed for developing a Class B explosion, (2) determining the effect of shipboard conditions (e.g., buffer zone size and ventilation) on the development of Class B explosions, and (3) determining the effectiveness of using water spray as a mitigating tactic.

3.0 APPROACH

In order to study Class B explosion phenomenon and assess the effectiveness of preventive tactics, an explosion had to be safely created in a repeatable test. As described above, there are two general scenarios that can lead to an explosion: (1) formation of a combustible fuel-air mixture in a normal oxygen environment, or (2) formation of a fuel-rich environment (insufficient oxygen) inside a closed fire space. In scenario 1, an ignition source is needed to produce an explosion, where as in scenario 2 both an ignition source and sufficient oxygen are needed. In both instances, hot surfaces from a preceding fire can be sufficient for ignition. Therefore, scenario 1 was determined to be too dangerous as a test scenario since the determining factor could not be fully controlled. The closed space presented an additional hazard of potentially producing explosion induced pressures above the capacity of the structure. Such explosions could cause serious damage to the ship/test compartment and injury to test personnel.

It was determined that a scenario 2 type explosion could be created in a safe test-oriented manner. Upon buttoning up a fire space, the fire extinguishes as it becomes oxygen starved. Fuel which continues to flow into the space will vaporize due to the hot gas and surface temperatures. Although the hot surfaces are sufficient ignition sources, the gases within the fire space will not ignite until additional air enters the space. From a testing standpoint, this is a very controllable parameter. For example, a door can be opened remotely, allowing a gravity current of colder air to flow into the fuel-rich, hot compartment while the hot fuel-rich gases flow out the top portion of the door (Fig. 1). The air and fuel-rich gases mix along the interface of the two flow streams. Ignition occurs once a flammable mixture is formed and it comes in contact with a sufficiently hot surface. The resulting deflagration will cause the gases to heat and expand within the fire space, thus forcing unburned gases out of the open vent ahead of the flame front. These gases will mix with additional air outside of the fire space. As the flame penetrates the doorway, it ignites the gases outside the space resulting in a fire ball and a blast

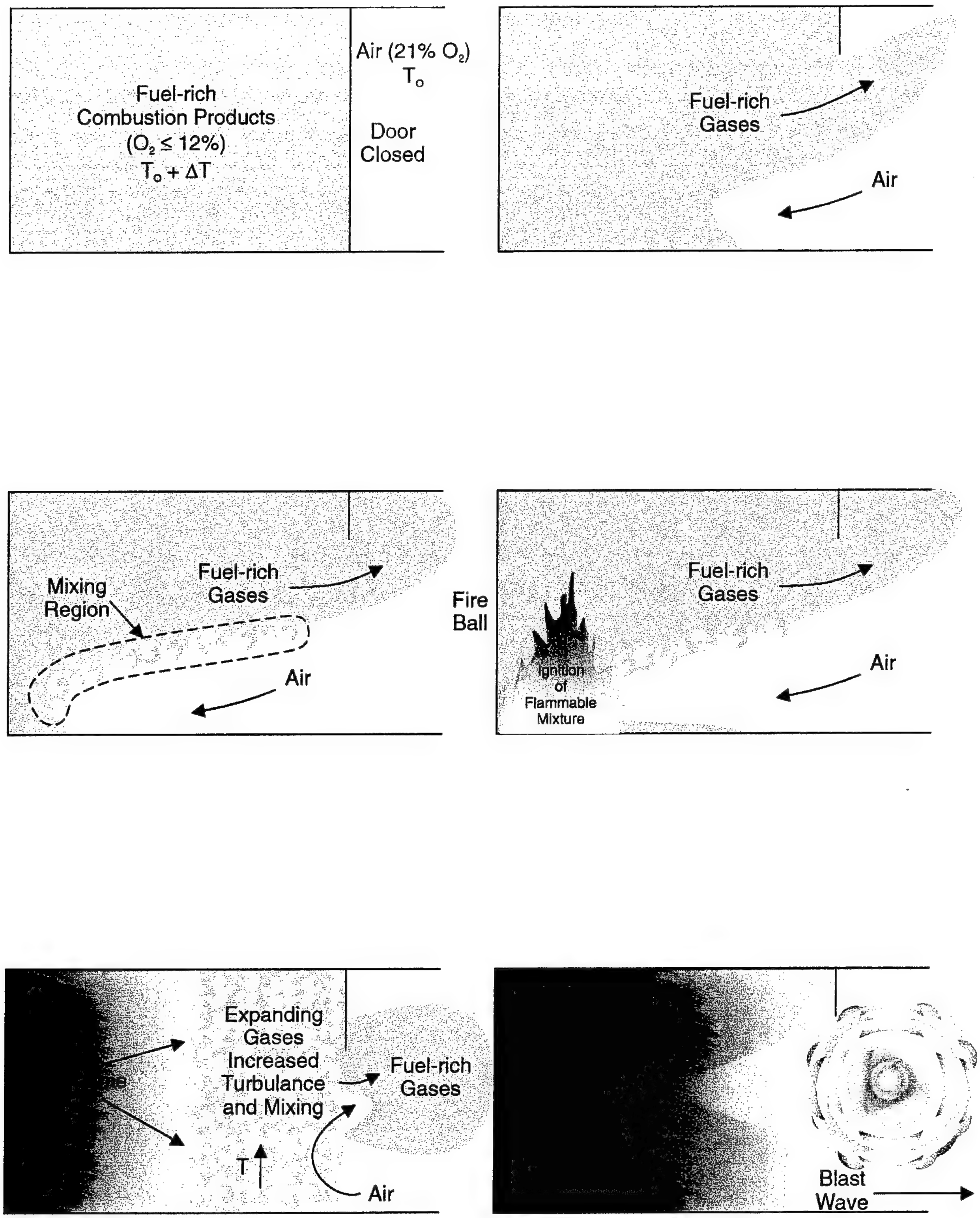

Fig. 1 – The development of a backdraft explosion.

wave. This explosion phenomenon from the gravity current to the blast wave is termed a backdraft.

The backdraft explosion phenomenon is not a restrictive case study. The two explosion scenarios discussed are similar in nature once ignition occurs. One difference is that in scenario 1 the space is more likely to be sealed when the explosion occurs than in scenario 2, thus, resulting in higher intensity blasts. The following description of a scenario 1 event explains how the two scenarios are related.

Consider that a fuel-line ruptures causing fuel to spray in a space. As fuel vapor/aerosol starts to fill the space, there will exist a fuel-rich region near the fuel source such that it is too rich to burn. However, a distance away from the fuel source, the fuel dissipates enough to mix with air and create a flammable mixture. At even a greater distance from the source, the fuel concentration is zero, and the concentration of oxygen is 21 percent. Ignition can only occur within the intermediate zone where the flammable mixture exists. Depending on the size of the space and the time duration, the space will continue to fill with fuel to form an increasingly larger flammable region. After a sufficiently long time, the space can become exceedingly fuel-rich and above the upper explosion limit (UEL). In this case (which is the same as scenario 2), ignition can not occur until additional air is introduced into the space. In both scenarios, once the fuel and air mix to flammable proportions, the ensuing deflagration and explosion are expected to be similar. The main difference will be that in scenario 1 the deflagration will occur in a primarily premixed system whereas in scenario 2 the deflagration is more similar to a diffusion flame. Since a premixed system will tend to produce higher intensity explosions, backdraft testing (scenario 2) represented a lower bounding case.

The general approach for Series 2 to 5 was to develop safe, reproducible backdraft scenarios which could be used as a basis to study the development and mitigation of Class B explosions onboard Naval ships. Factors that were studied included (1) the amount of fuel needed for an explosion, (2) the effect of buffer zone size on the development of a backdraft explosion, (3) the effect of creating a dead-air buffer zone on the development of a backdraft explosion, and (4) the amount of water needed to mitigate a backdraft from occurring. For safety reasons, the first tests (Series 2) were conducted outside in a compartment that vented directly to weather. Upon completion of these tests, experiments were conducted onboard the ex-USS SHADWELL.

Initial tests (Series 2A) were conducted at the Naval Research Laboratory, Chesapeake Beach Detachment (CBD) during the period of March 22-28, 1995. These tests were successful in creating safe backdraft scenarios. However, the ability to create a suitable, reproducible backdraft test was not achieved. Therefore, a second set of tests at CBD (Series 2B) was conducted May 8-12, 1995. The main purpose of the CBD series was to characterize the necessary conditions for creating a safe backdraft explosion test. The effectiveness of using various amounts of water spray injection was also studied during these tests.

The test scenarios developed at CBD during Series 2 were used to develop similar backdraft tests onboard the ex-USS SHADWELL. The first tests on the ship (Series 3) were conducted from June 19-30, 1995. Development of backdraft conditions onboard a ship presented an increased hazard compared to the tests performed in the open at CBD. The additional confines of the ship were expected to produce higher maximum pressures within the main fire space as the backdraft deflagration occurred. Therefore, the primary objective of Series 3 was to incrementally change the fuel loading in the fire space until a safe, reproducible backdraft test scenario was developed. This test scenario was then used as a baseline for evaluating various buffer zone ventilation schemes, such as the establishment of a dead-air zone.

Test Series 4 was conducted aboard the ex-USS SHADWELL from July 31 to August 11, 1995. These tests focused on studying the effect of reducing the size of the buffer zone with respect to the fire space. Both fully ventilated and dead-air conditions were evaluated. The use of water mitigation was also investigated.

Test Series 5 was conducted aboard the ex-USS SHADWELL from September 11-15, 1995 and served primarily as a firefighting and tactics workshop. The objectives of the workshop were (1) to review and demonstrate lessons learned during the Series 1-4 testing, and (2) to discuss and solicit recommendations for the FY 96 Machinery Space Fire Doctrine testing. The fire test demonstrations consisted primarily of repeat conditions studied in Series 3 and 4. The workshop participants included members representing NAVSEA 03G, CINCLANTFLT NDI, ATG LANT, ATG MIDPAC, CINCLANTFLT PEB, CINCPACFLT PEB, MSC Fire School, and SWOSCOLCOM.

4.0 EXPERIMENTAL SETUP AND PROCEDURE FOR SERIES 2

Figs. 2 and 3 show a plan and elevation view of the overall test compartment and layout of instrumentation. The test compartment was a steel structure measuring 2.44 m wide by 4.88 m deep by 2.44 m high (8 ft wide by 16 ft deep by 8 ft high) with a volume of 29 m^3 (1024 ft^3). The only ventilation to the space was through a door on the west end of the compartment. The door was 0.66 m wide by 1.68 m tall (26 in. by 66 in.) and was positioned on the left side of the west wall. A 90 degree full cone, fine atomization fuel nozzle (Bete P-series) was positioned in the back of the compartment, 0.9 m from the north and east walls. Except for tests BD2-8, the same nozzle and fuel supply system was used for both the preburn fire and the secondary fuel injection. The low flow nozzles used provided accurate control over the amount of fuel injected into the compartment. The fuel mass supply rate was calculated based on the pressure of the fuel at the nozzle and the nozzle flow coefficient. The nozzle flow coefficients were obtained by multiplying the manufacturers flow coefficient based on water by the square root of the ratio of the specific gravity of water to the specific gravity of the fuel. A flow calibration of this system using these flow coefficients is presented in reference (4)).

The compartment was instrumented with two thermocouple trees, a bulkhead thermocouple, a pressure transducer, and two gas sampling lines for oxygen concentration measurements. Other data collection consisted of still and video photography. Two video cameras were used to capture both a west-side view (i.e., a view looking at the door) and a north-side view of the compartment.

In general, tests consisted of establishing a hot, vitiated (less than 10 percent O_2) environment inside the compartment by burning a No. 2 diesel spray fire and securing the fuel and door before the fire self-extinguished. A known amount of No. 2 diesel fuel was then injected into the compartment and allowed to vaporize and mix with the combustion gases. After the secondary fuel was secured, the door was remotely opened to induce the backdraft. For the tests aimed at studying backdraft mitigation, water was sprayed into the center of the compartment between the time the secondary fuel was secured and the door was opened.

The development of a safe backdraft experiment was dependant on maintaining the oxygen concentration below the lower oxygen index (LOI) while flowing the secondary fuel into the pre-heated compartment (i.e., after the initial fire was extinguished). The objective was to avoid the creation of a fuel/air mixture that was within the lower and upper flammability limits. A worst case scenario would have consisted of developing such a fuel/air mixture and having it ignite while the compartment was closed.

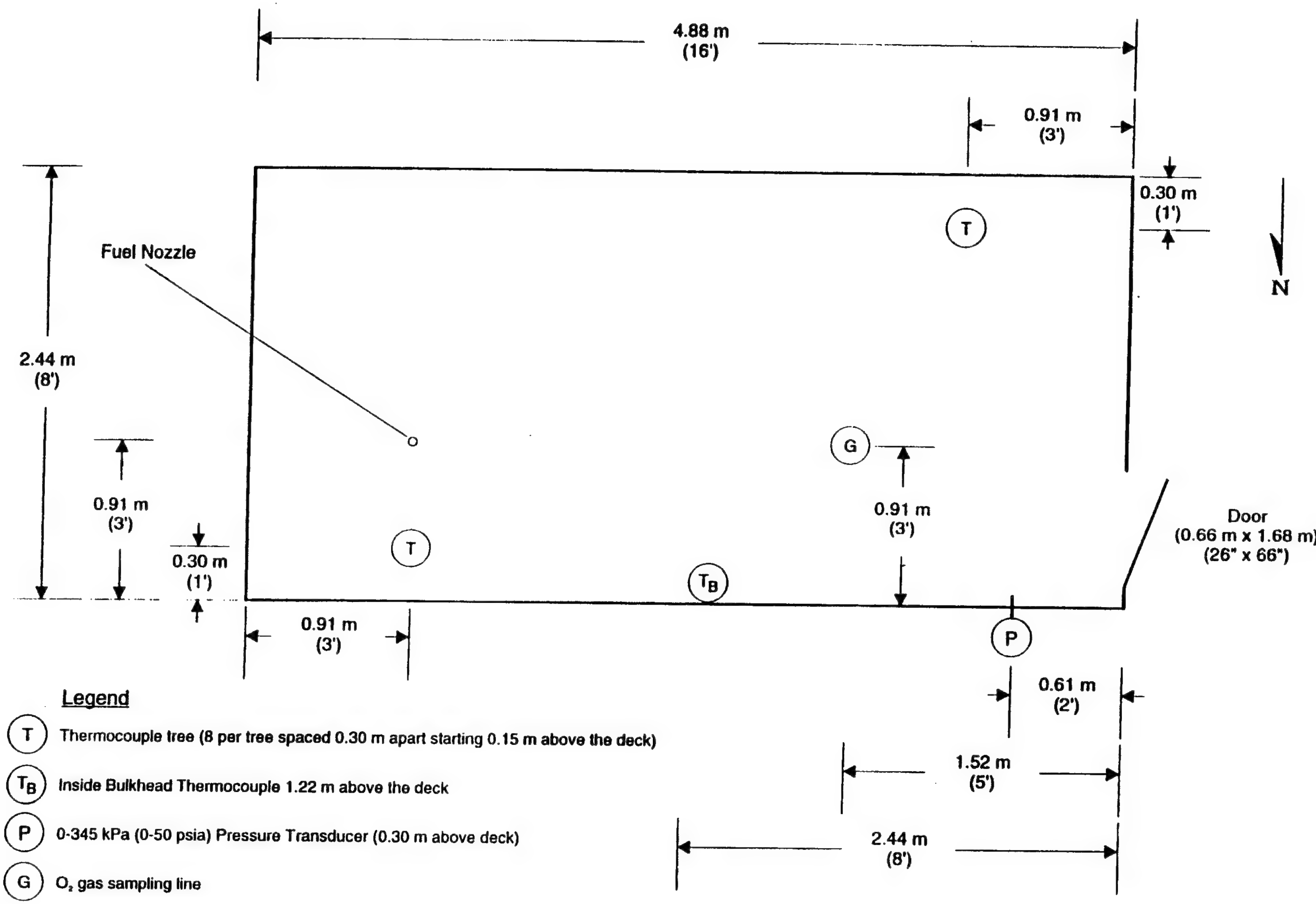

Fig. 2 Schematic of Backdraft Test Setup (plan view)

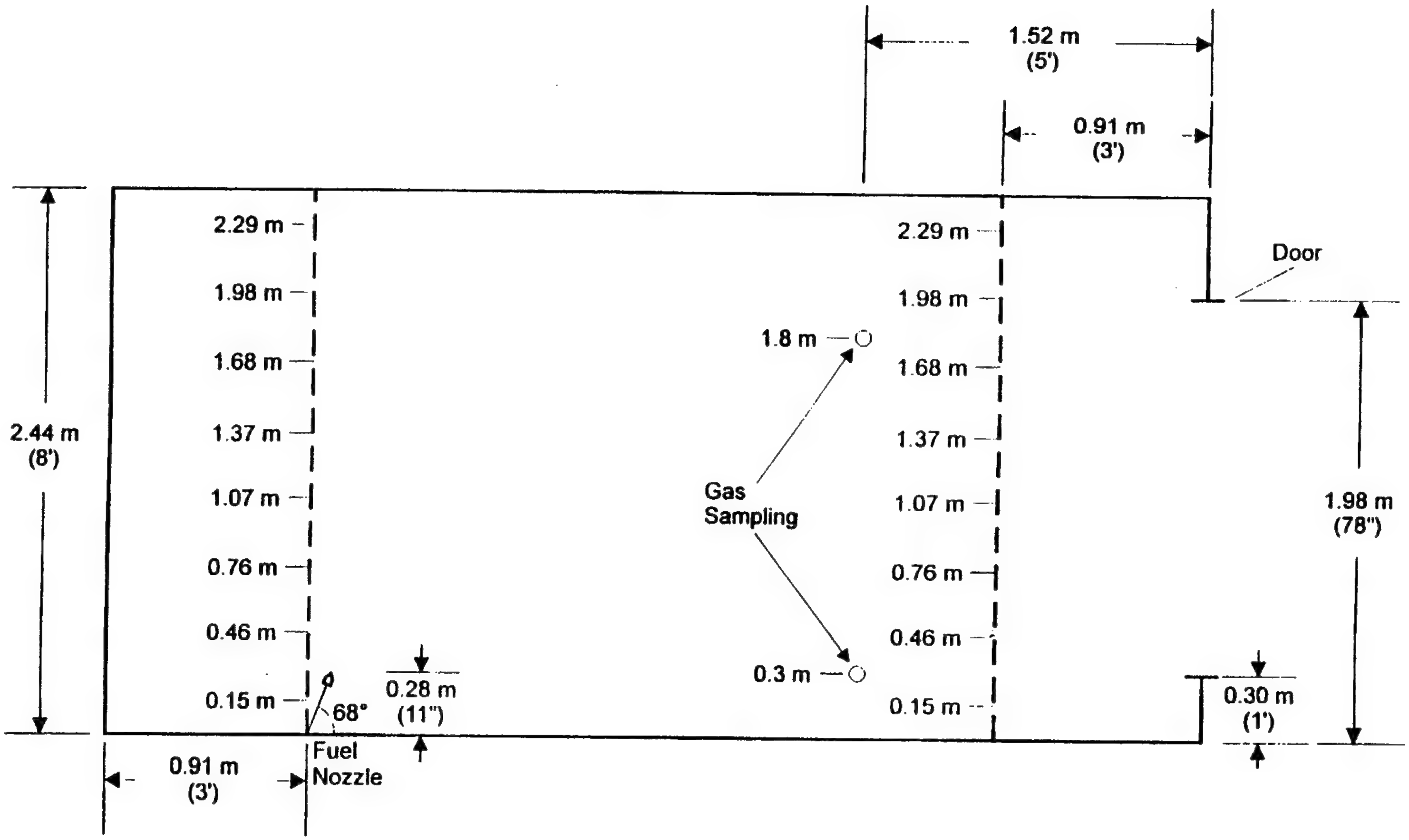

Fig. 3 Schematic of Backdraft Test Setup (elevation view)

The test scenarios were developed on the premise of burning a stoichiometric fire so that there was minimal excess air or fuel in the compartment at the time the door was closed. Using the ventilation parameter, $Ah^{1/2}$ (A is area of opening and h the height of the opening), to determine the air flow rate into the compartment and a stoichiometric fuel-to-air ratio of 0.068 the design fire was 2.1 MW (3.6 lpm (0.96 gpm)). Upon reaching steady-state temperatures and oxygen concentrations of about 3 percent or less in the upper layer, the door was secured. This preburn period was about 15 minutes. The fuel flow was secured 5 s after the door was closed. This small delay allowed the fire to further consume the remaining oxygen while assuring that excessive fuel was not sprayed into the compartment. The door was closed and secured by wedging a pole between the door and a stop. As the test series progressed, the door began to warp creating gaps between the door and the compartment. A gasket of ceramic fiber blanket (Fiberfrax) was used to seal the door. As a result, the space was not air tight. Typically, there was noticeable smoke leakage around the door during the secondary fuel injection and the subsequent hold time before the door was opened.

The secondary fuel flow into the compartment was injected 60 seconds after the initial fuel flow was secured. The typical injection time was 60 seconds. The 60 second delay was to insure that the fire was out and to allow the compartment gases to mix. Due to the transport time in the gas sampling system, this time was also needed to insure that O_2 concentrations were below the LOI (typically about 12 percent). Measured concentrations were below 10 percent by volume before secondary fuel was injected.

After the secondary fuel injection was complete, the door was opened to induce the backdraft phenomenon. The door was opened remotely using two ropes, one to dislodge the wedged pole and one to pull the door open. Several delay times between the end of secondary fuel flow and the opening of the door were studied (0, 10, 30, 120, and 240 s). The majority of tests were performed with a 120 s delay. For the water mitigation tests, this delay provided enough time for water to be sprayed into the center of the compartment between the time the secondary fuel was secured and the door was opened. Typically, water was sprayed using a TF10FC nozzle (Bete) for a 60 second period starting 30 seconds after the secondary fuel was secured. This water injection system provided an accurate means for quantifying the water used while obtaining good dispersion within the space.

For each series, the first tests performed consisted of burning the initial fire and proceeding with the standard procedure except that no secondary fuel was injected. These tests were used to check the logistics of safely conducting the tests and to verify the success of the initial design fire to reduce the O_2 concentration and achieve steady-state conditions. The volume of secondary fuel injected was systematically increased for subsequent tests. For Series 2 tests, the amount of fuel ranged from 1 to 7 liters (0.25 to 1.9 gal).

5.0 EXPERIMENTAL SETUP AND PROCEDURE FOR SERIES 3-5

The tests conducted aboard the ex-USS SHADWELL were conducted in spaces 3-16-1 (designated as a Pump Room) and 3-16-01L (designated as an Emergency Generator Room (EGR)) (Fig. 4). Over the course of these test series, three different buffer zone configurations were studied: (1) Buffer Zone EGR , (2) Buffer Zone 1, and (3) Buffer Zone 2. These three configurations are shown in Figs. 4-6, respectively. Buffer Zones 1 and 2 were created using 2x6 studded walls covered with half inch plywood and half inch gypsum wall board. All joints were spackled or caulked so that the spaces were well sealed. Table 1 shows the volume of each buffer zone configuration.

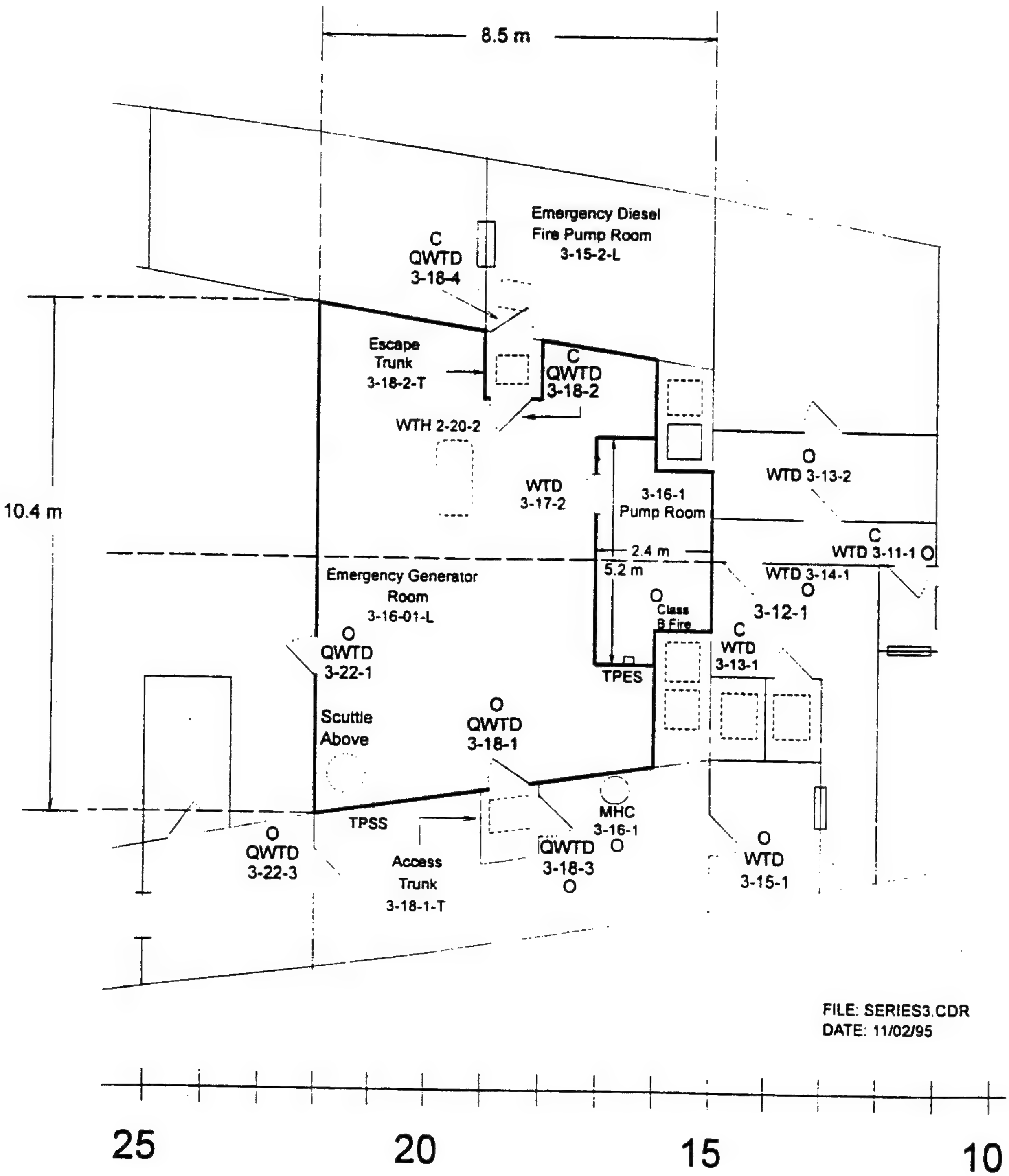

Fig. 4 – Third deck plan view showing test closure for Buffer Zone EGR. O indicates open, C indicates closed.

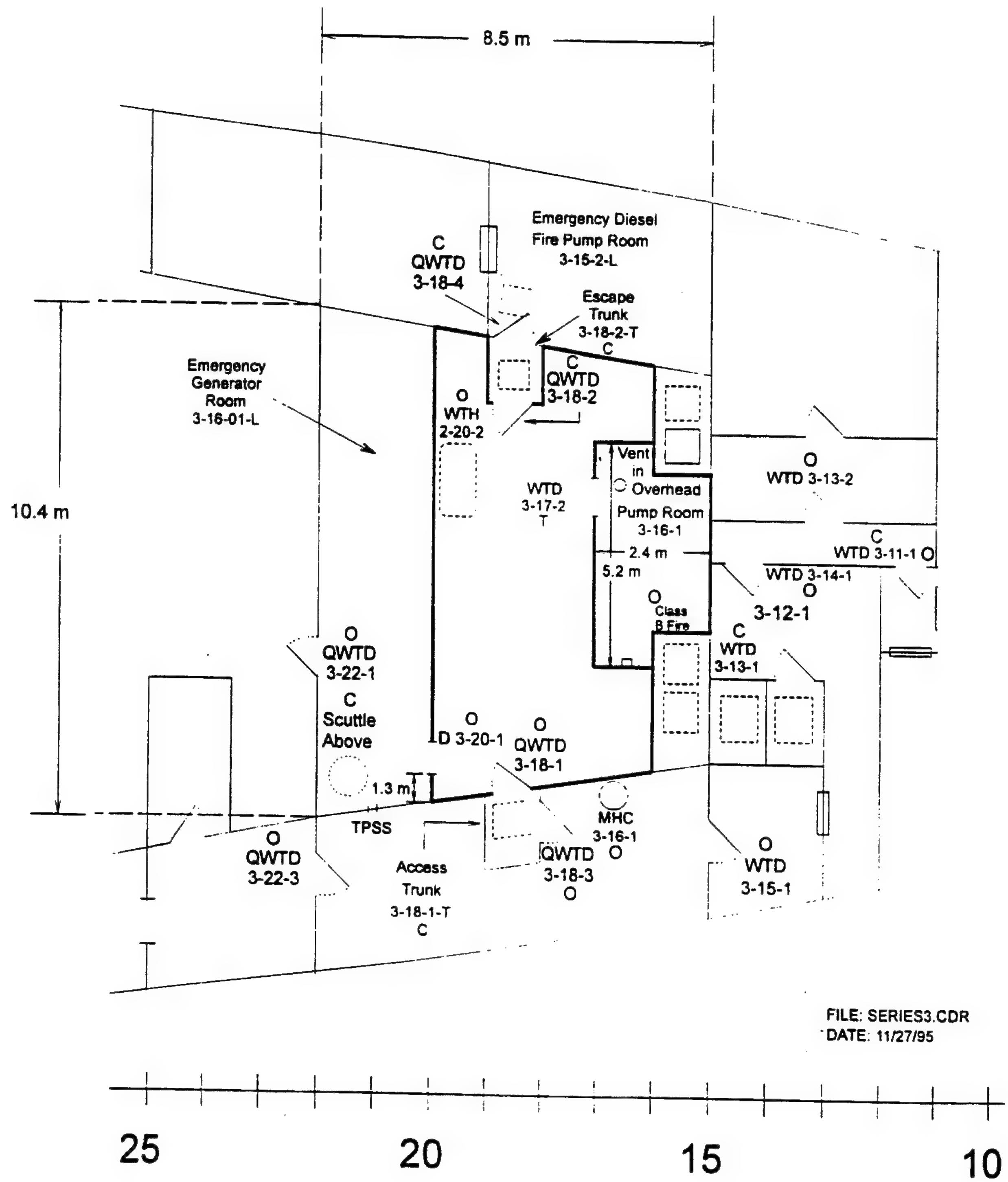

Fig. 5 – Third deck plan view showing test closure for Buffer Zone 1. O indicates open, C indicates closed, T indicates test dependent.

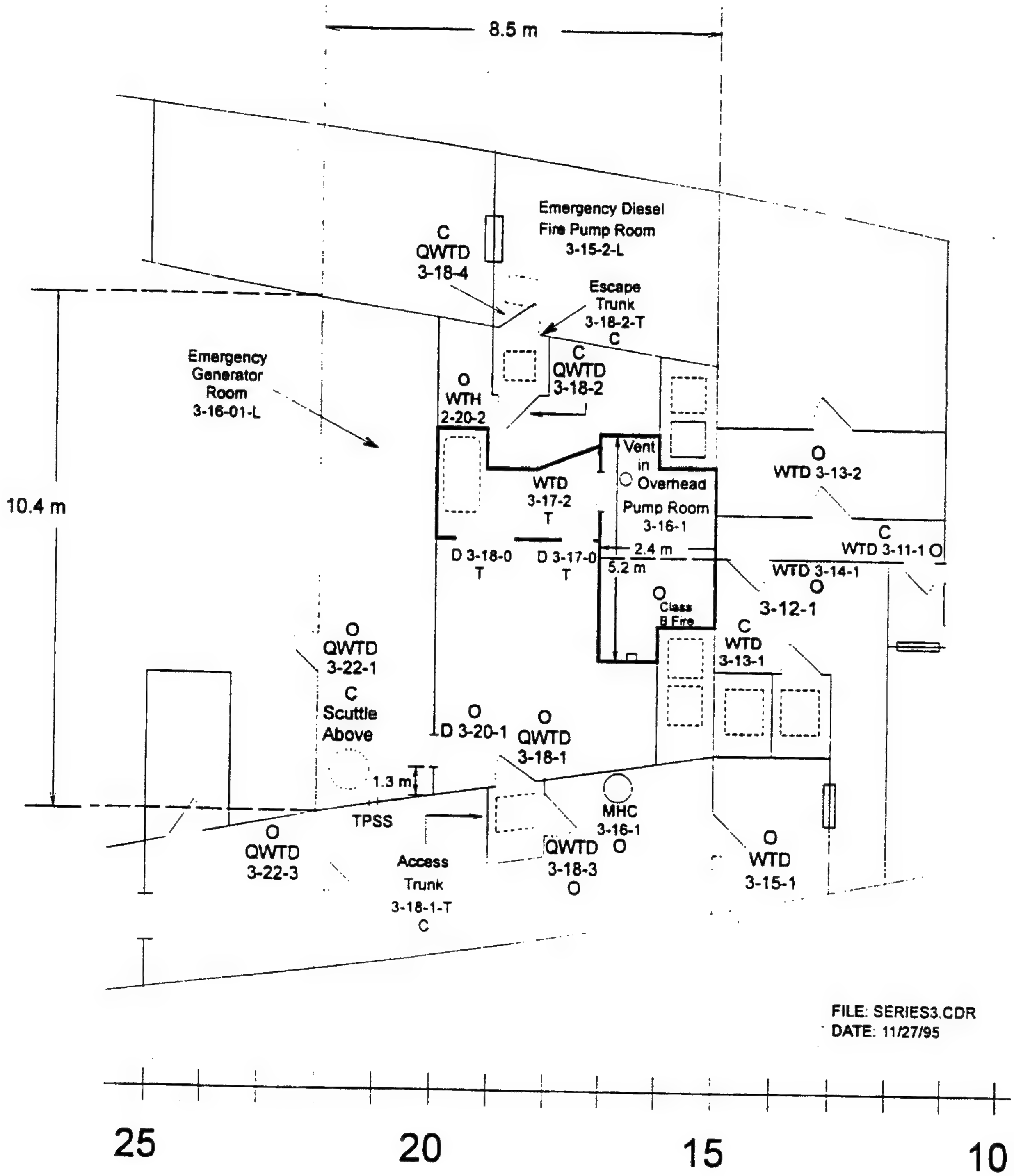

Fig. 6 – Third deck plan view showing test closure for Buffer Zone 2. O indicates open, C indicates closed, T indicates test dependent.

Table 1. Buffer Zone Configurations Studied in Series 3 to 5

Buffer Zone	Size		Primary Door
	(m^3)	(ft^3)	
EGR	191	6729	QWTD 3-22-1
1	104	3657	D 3-20-1
2	20	715	D 3-17-0

The general approach for each buffer zone was to study the development of a backdraft explosion under two buffer zone conditions: (1) full ventilation and (2) dead-air. Ventilation through the test area was controlled via fans E1-15-1 and E1-15-2 drawing through ventilation ducts at 2-15-1 and 2-15-2 and exhausting to weather. Fig. 7 shows the location of the ventilation ducts in the second deck space directly above the third deck test area. For all buffer zone configurations fire effluent was exhausted through WTH 2-20-2 and then through the second deck ventilation ducts. Full ventilation consisted of operating both E1-15 fans at 100 percent with WTH 2-20-2 and the primary buffer zone door open (see Table 1). A dead-air space was created within the buffer zone by securing both E1-15 fans and covering WTH 2-20-2 and the primary buffer zone door with a smoke blanket and curtain, respectively. Several auxiliary ventilation schemes were also used during a few tests. These included operating the E1-15 fans at reduced capacity and also using a standard desmoking setup. The desmoking setup consisted of stacking 2 box fans within WTD 1-15-2 and drawing the fire gases in the second deck up through WTS 1-19-2, through the ship fitter's shop and out onto the foc'sle.

During the preburn period, full ventilation was used in order to supply sufficient air for maintaining the fire and as a safety measure. Maintaining optimum visibility was critical as the safety team needed to monitor the fire and maneuver in the space while securing the fire door. The test closure plans are indicated on Figs. 4-7. In general, the closure plan was the same for each buffer zone configuration. Except for QWTD 3-18-3 and D 3-18-0, all closures remained the same throughout the entire test. QWTD 3-18-3 was closed but not dogged during the procedure of opening the fire door to start the backdraft explosion. All doors aft of frame 3-22 remained open to weather to provide the maximum ventilation opening for diffusing the explosion.

The small size of Buffer Zone 2 and the position of door 3-17-0 with respect to the fire door, produced high air velocities by the fire door. This high velocity flow disrupted the typical bidirectional flow pattern at the fire door which subsequently disrupted the preburn fire. In order to obtain a more satisfactorily burning fire, a large double door (D 3-18-0) was opened up during the preburn. Fig. 8 shows a detailed schematic of Buffer Zone 2 with the two doors. The double door opening measured 1.22 m by 2.13 m tall (48 by 84 in.). All other buffer zone doors were 0.66 m by 1.68 m tall (26 by 66 in.) (i.e., a standard Navy door).

The primary test setup consisted of a No. 2 diesel spray fire in the Pump Room which exhausted into the adjoining buffer zone through WTD 3-17-2. The Pump Room had an open volume of approximately 35 m^3 (1234 ft^3) with one main opening through WTD 3-17-2. Detailed drawings of the Pump Room showing the obstructions in the space due to large ventilation ducts are included in reference (4)). As shown in Fig. 5, there was a 0.3 m duct in the overhead on the port side of the space. This duct remained closed via a butterfly damper. The duct was initially installed to allow venting of over pressure during water injection from the fire space to

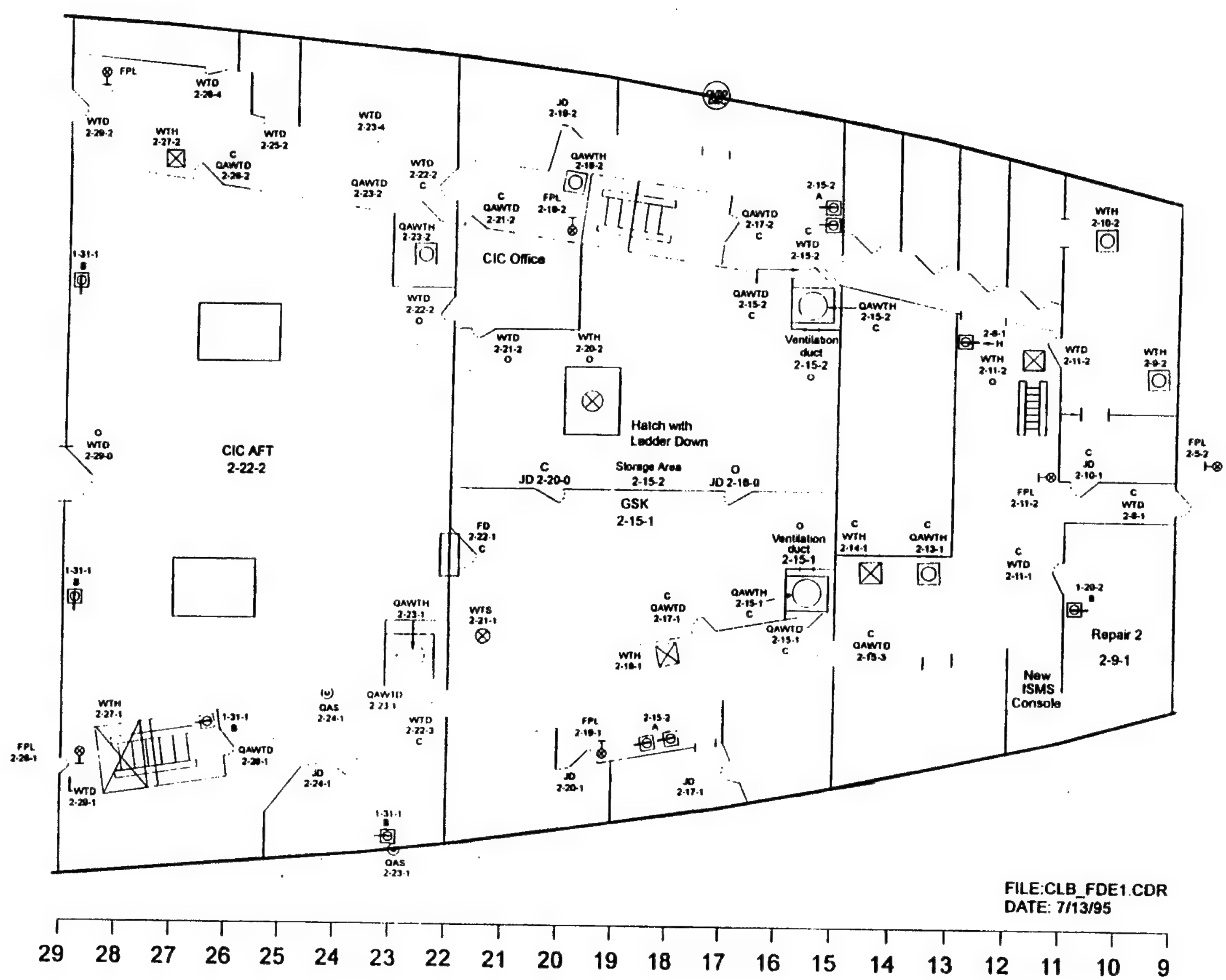

Fig. 7 – Second deck plan view showing test closure, O indicates open, C indicates closed.

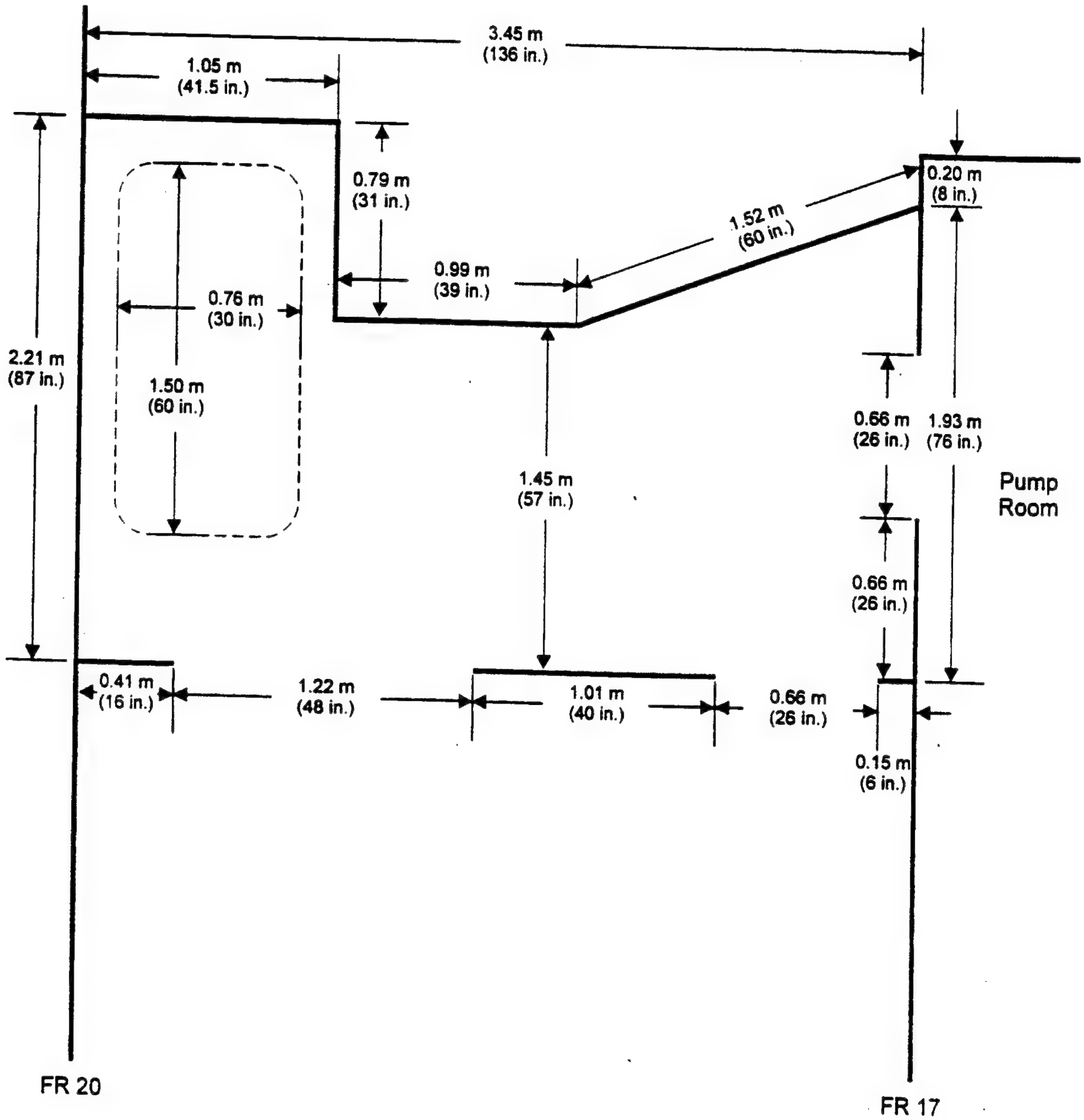

Fig. 8 – Detailed Schematic of Buffer Zone Configuration 2.

the second deck space above it. However, there was sufficient leakage in the compartment that opening the duct was never required. All possible efforts were made to maintain the compartment near air tight, however the thermal stress of testing made this a continuous task as the door warped and cracks formed. In general, leakage was minimized; and in cases where a substantial leak did occur the test results indicated it.

The same test procedure was used for Series 3-5 as used in Series 2B. Tests consisted of establishing a hot, vitiated (measured O_2 concentrations less than 10 percent) environment inside the compartment by burning a No. 2 diesel spray fire and securing the fuel and door before the fire self-extinguished. A known amount of No. 2 diesel fuel was then injected into the compartment and allowed to vaporize and mix with the combustion gases. After the secondary fuel was secured, the door was remotely opened to induce the backdraft. Similar to the majority of Series 2 tests, there was a 60 second delay between closing the door and starting the secondary fuel injection and a 120 second time delay between the end of secondary fuel flow and the opening of the door. For the tests in which water was injected into the space, this delay provided enough time for water to be sprayed into the center of the compartment between the time the secondary fuel was secured and the door was opened. Water was sprayed using a TF8FC nozzle (Bete) for a 30 to 60 second period starting 30 seconds after the secondary fuel was secured. This water injection system provided an accurate means for quantifying the water used while obtaining good dispersion within the space.

Both the fuel for the preburn fire and the secondary fuel injection were sprayed using a 90 degree full cone, fine atomization nozzle (Bete P66). The nozzle was oriented straight up and was located 0.3 m above the deck in the starboard side of the fire compartment. The procedure for measuring the flow rate of fuel is the same as that discussed for Series 2 tests. The standard preburn consisted of a 40 grams/sec flow rate (1.7 MW) for 7 minutes followed by a 45 grams/sec flow rate (1.9 MW) for a total preburn time of 15 minutes. Since the fire door dimensions were the same for these tests as in the CBD tests, the stoichiometric design fire was calculated to be 2.1 MW. However, due to the configuration of the fire space and the overhead obstructions, this size fire was difficult to maintain. Even with the leaner fires used, gas concentrations indicated a fairly high degree of incomplete combustion. Carbon monoxide concentrations were as high as 3.5 to 4 percent by volume. The two step fueling procedure provided a good start up fire under cold conditions. After the space heated, the fuel flow was increased to quicken the time toward steady-state conditions. The formation of a red hot zone on the FR 17 bulkhead was a good indicator of when the space was sufficiently hot. As discussed below, the fuel mass fraction is dependant on the average temperature of the space.

Figs. 9-13 show the instrumentation used in the third and second deck test areas, for each of the three buffer zone configurations. Measurements consisted of air and bulkhead temperatures, pressures between spaces and ventilation openings, fuel supply pressure, and gas concentrations high and low in both the Pump Room and the buffer zone. Other documentation consisted of video photography. The camera locations and view angles are also shown in Figs. 10-12. Key measurements are discussed below.

Gas analyzers were used to continuously monitor the gas concentrations of carbon monoxide, carbon dioxide and oxygen in the fire compartment and in the Emergency Generator Room. Analyzers consisted of Beckman model 865 for carbon monoxide and carbon dioxide measurements, and Beckman model 755 for oxygen measurements. Gas sample lines were located at

(1) low in the fire space at 3-16-2, 0.3 m above the deck,

KEY

T_O	Thermocouple overhead - one pair 6" and 18" below the overhead
T_A	Thermocouple air
T_B	Bulkhead thermocouple - on side noted, 60 in. above the deck
T_D	Deckmount thermocouple - one thermocouple located on the deck on the side indicated by the drawing
T	Thermocouple tree (320, 274, 229, 183, 137, 92, 46 cm) (126, 108, 90, 72, 54, 36, 18 in.)
G	Continuous Gas sampling point (CO, CO_2, O_2)
GS	Grab sampling point
C $\rightarrow$	Camera
P_Δ	Differential pressure
B	Bidirectional probe
ODM	Optical Density Meter

Fig. 9 - Instrumentation key for Figures 10-12.

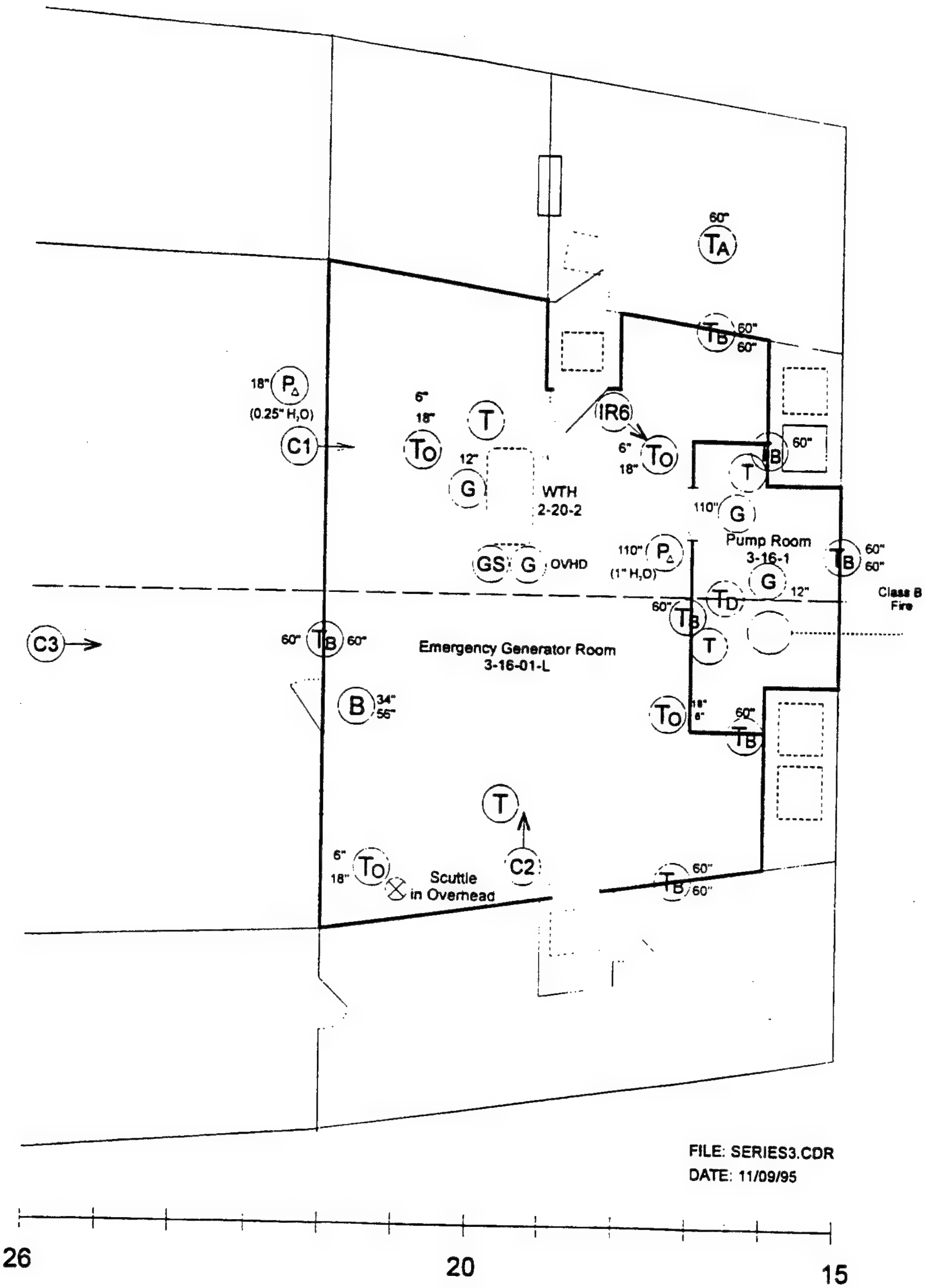

Fig. 10 - Third deck instrumentation for Series 3 Buffer Zone EGR tests.

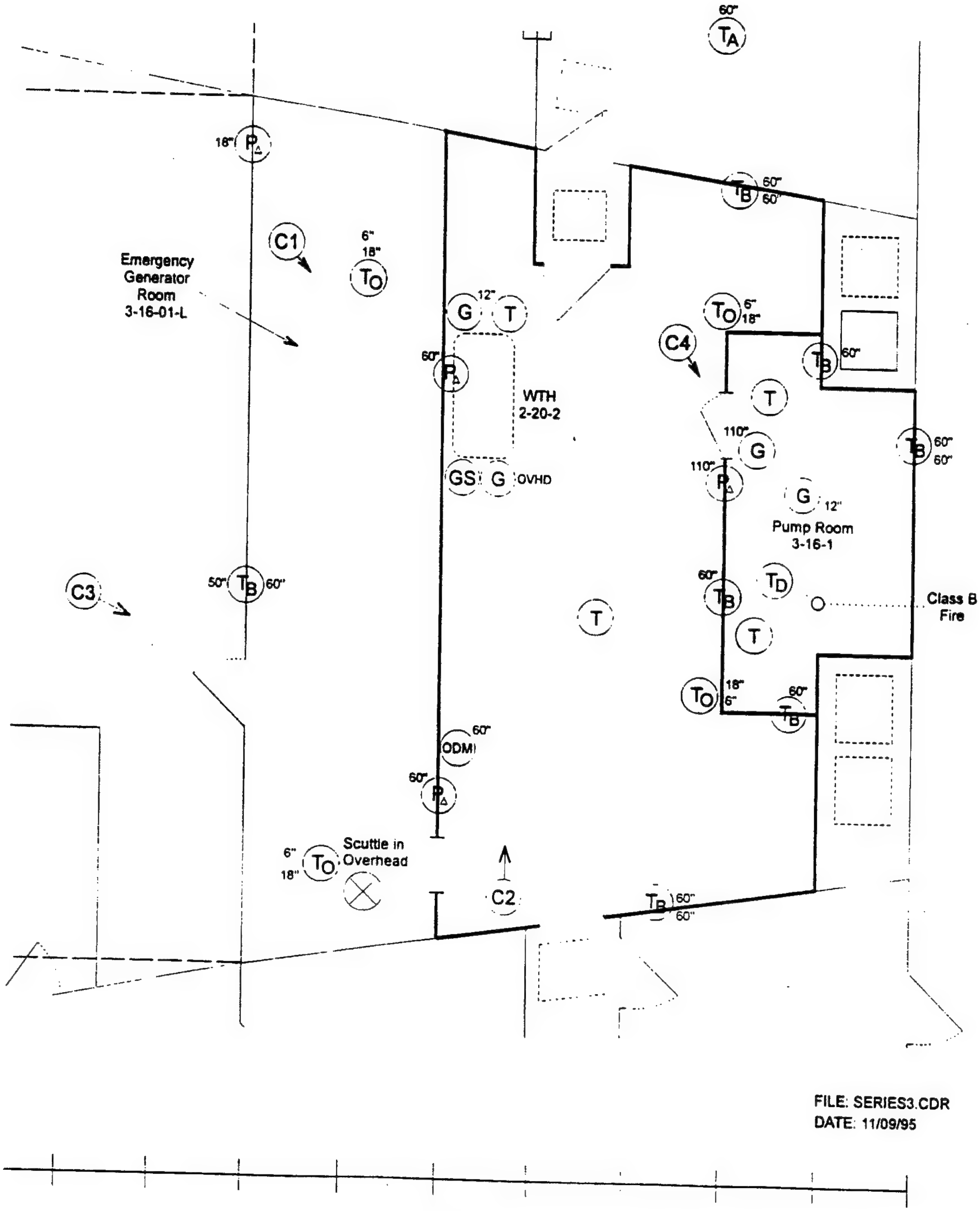

Fig. 11 - Third deck instrumentation for Series 4 and 5 Buffer Zone 1 tests.

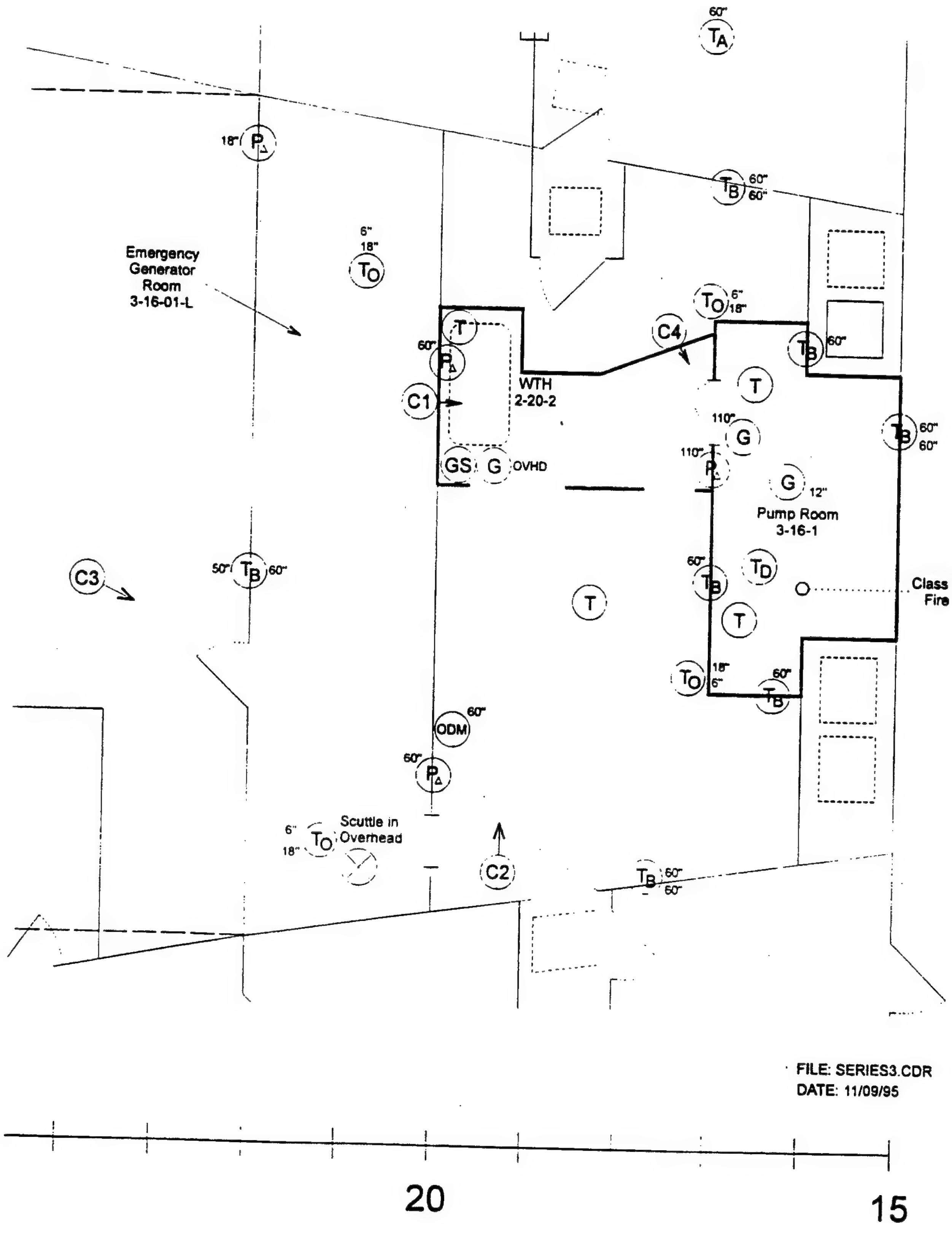

Fig. 12 - Third deck instrumentation for Series 4, Buffer Zone 2.

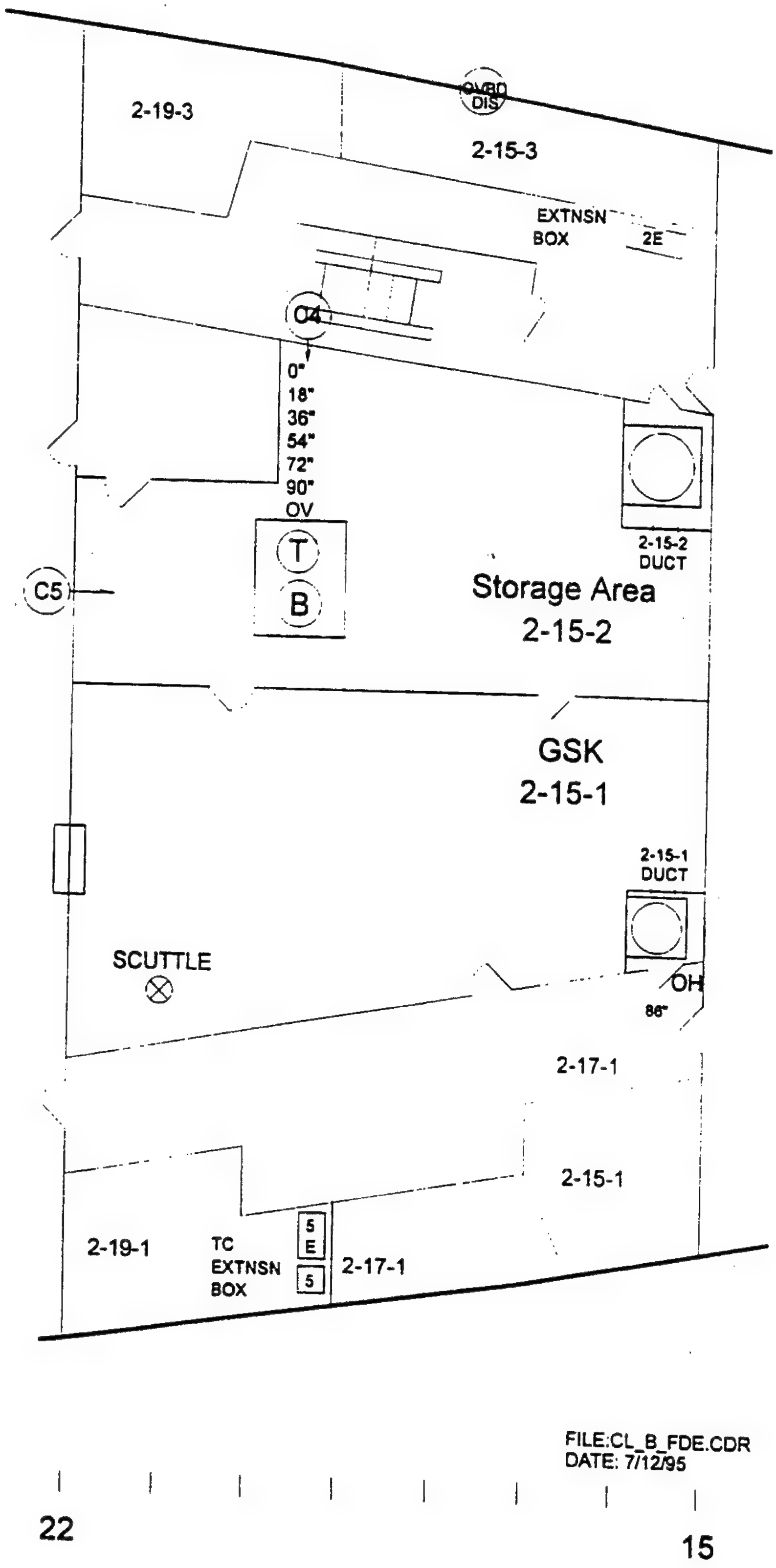

Fig. 13 - Second deck instrumentation for Series 3-5 tests.

(2) high in the fire space at 3-16-2, 2.8 m above the deck,

(3) low in the buffer zone at 3-20-2, 0.3 m above the deck, and

(4) high in the buffer zone at 3-20-2, in the overhead centered on the starboard side of WTH 2-20-2.

All gas samples were filtered and passed through an impingement-type water trap. In addition, all samples were passed through cold traps to remove any remaining water. The 90 percent response time of the four sampling systems ranged from 60 to 92 seconds.

Selected grab samples of the buffer zone were taken and analyzed by gas chromatography. Samples were drawn from the same location below the hatch as the continuous gas sampling point high in the buffer zone.

Type K, inconel-sheathed thermocouples were used to measure gas and bulkhead temperatures. Key thermocouples include the following:

(1) A vertical string located inside the fire space at FR 3-16-2 with thermocouples at 46 cm, 92 cm, 137 cm, 183 cm, 229 cm, 274 cm, and 320 cm (18 in., 36 in., 54 in., 72 in., 90 in., 108 in., and 126 in.) above the deck.

(2) A vertical string located in the fire space at FR 3-17-1 with thermocouples at 46 cm, 92 cm, 137 cm, 183 cm, 229 cm, 274 cm, and 320 cm (18 in., 36 in., 54 in., 72 in., 90 in., 108 in., and 126 in.) above the deck.

(3) A vertical string located in all buffer zones at FR 3-19-2 to the port side of WTH 2-20-22 with thermocouples at 46 cm, 92 cm, 137 cm, 183 cm, 229 cm, 274 cm, and 320 cm (18 in., 36 in., 54 in., 72 in., 90 in., 108 in., and 126 in.) above the deck.

(4) For Buffer Zone EGR, a vertical string located at FR 3-19-1 with thermocouples at 46 cm, 92 cm, 137 cm, 183 cm, 229 cm, 274 cm, and 320 cm (18 in., 36 in., 54 in., 72 in., 90 in., 108 in., and 126 in.) above the deck. For Buffer Zone 1 and 2 this string was located at FR 3-18-1 inward toward centerline.

(5) Bulkhead thermocouples were placed on all six boundaries of the fire compartment. Bulkhead thermocouples were located near the center of each side of the space at 1.52 m (60 in.) above deck. A deck thermocouple was located in the center of the space and above this, the overhead metal surface temperature was made on the underside of the deflection plate shielding the overhead duct work from the fire.

Pressure differentials were measured at various locations for the purpose of quantifying the blast pressure of the explosion across the fire boundary and the buffer zone boundaries. Due to the high temperatures and sooty environment the pressure transducers needed to be remote from the test space. The transducers were connected to the pressure ports using 0.6 cm diameter copper tubing. Due to the highly transient nature of the blast wave and the damping effect of the tubing, it was realized that the pressure measurements would be less than the actual pressure pulse. The leading transducer manufacturers were unable to give even an

estimate to the magnitude of this type of measurement error. Despite this limitation, it was expected that the pressure measurements would provide useful information to the relative intensity of explosions for the different conditions studied. However, as discussed below, a lack of reproducibility and the overranging of some instruments precludes any conclusive trends.

6.0 RESULTS

6.1 Series 2A

Table 2 shows a summary of the test scenarios conducted. This table lists the test name, the nominal fuel mass fraction (defined below), the total time the door was closed, the delay time between securing the secondary fuel and opening the door, the resulting outcome, and general comments. The bold division lines group tests which were essentially repeat tests of the same scenario. The resulting outcome describes what happened outside of the door. In some cases, there was a deflagration in the compartment (noted by a peak rise in temperature and pressure) without a fire ball outside of the compartment. These tests were characterized by either the ejection of a large ball of smoke (2 to 5 m in diameter) or a roll out of flame under the soffit. Fig.14 shows a photograph of a smoke ball forming outside the fire door for test BD09. The second tier compartment seen in the photograph was an extraneous structure as it was isolated from the test compartment below. The formation of a smoke ball was very similar to a backdraft explosion (except without flame outside the compartment) in that there was an audibly and visually distinct pressure pulse which had thrust the gases out of the compartment to form the ball of smoke. The formation of a fire ball can be seen in Figs. 15 and 16. Fig. 15 shows an east facing view (Fig. 2) of the test compartment with a fire ball forming outside the door (test BD21). The maximum size of this fire ball was about 4.3 m (14 ft) in diameter. Fig. 16 shows a south facing view of a fire ball extending from the fire compartment door which is on the left edge of the photograph (test BD75). In some cases, the fire ball was preceded by a ball of smoke and/or an extension of flame out of the door.

The nominal fuel mass fraction is an important parameter which will be referred to throughout this report. The nominal fuel mass fraction, Y_f, is defined as ratio of the mass of fuel injected into the fire compartment to the total mass in the compartment. An overly simplified expression for Y_f is:

$$Y_f = \frac{m_{fuel}}{m_{mix}} \qquad (1)$$

where

$$m_{mix} = V_{comp}\,\rho(T_{comp})_{air} \qquad (2)$$

where the mass of the mixture equals the product of the compartment volume and the density of the mixture which is assumed to be that of air at the average temperature of the compartment gases. Since the injected fuel mass skews the mixture density from that of air, a more refined method for computing the fuel mass fraction is via an iterative calculation assuming the initial

Fig. 14 - A photograph of a smoke ball forming outside the fire door for test BD09.

Fig. 15 - A photograph of the formation of a fire ball during test BD21.

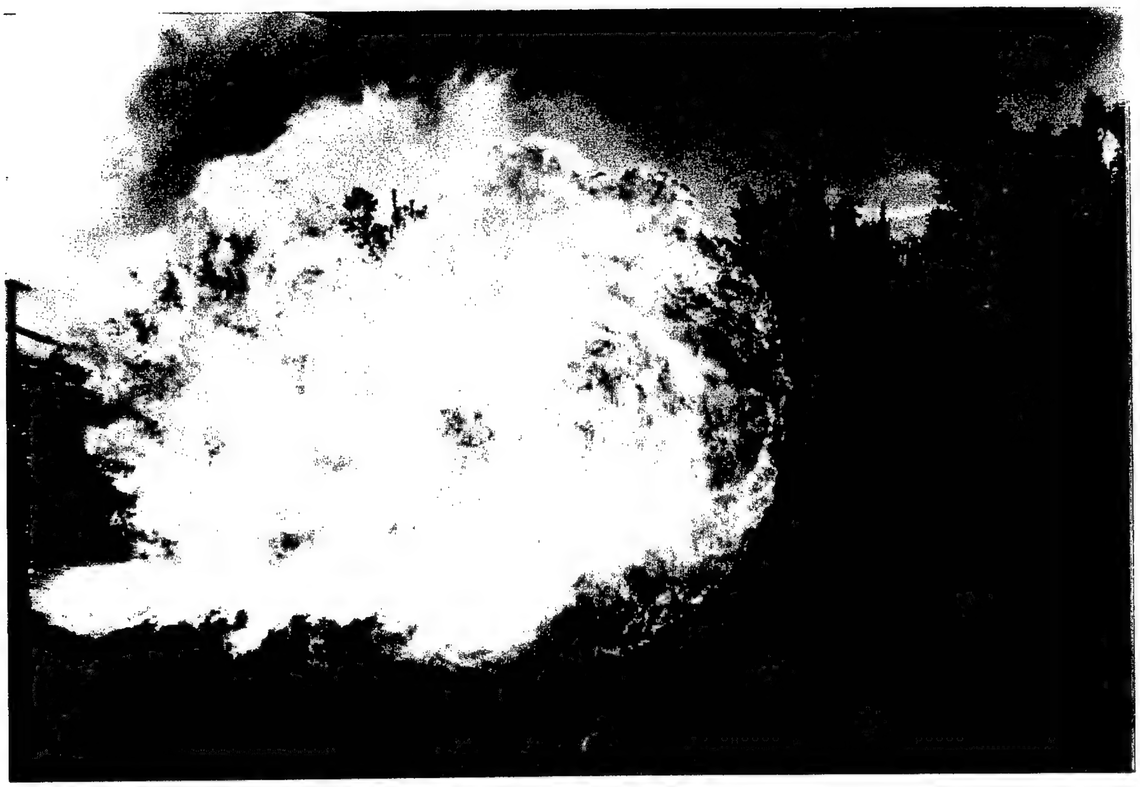

Fig. 16 - A side view photograph of a fire ball extending from the fire. compartment door (leftmost edge) for test BD75.

Table 2. Summary of Series 2A Test Scenarios

Test	Fuel Mass Fraction	Time (sec) Door was Closed	Time (sec) b/n securing fuel and door open	Outcome	Comments
BD1	NA	NA	NA	Nothing	
BD2	NA	NA	NA	Nothing	
BD3	0.053	133	32	Nothing	
BD4	0.063	130	29	Nothing	
BD5	0.090	131	31	Nothing	
BD6	0.066	131	25	Flame Only	repeat of 4 with igniter
BD7	0.101	101	0	Fire Ball	repeat of 5 with no delay
BD8	0.116	121	10	Nothing	leak in secondary fuel line - fuel mass fraction suspect, igniter on when door open
BD9	0.116	108	10	Smoke Ball	repeat of 8 - Igniter on when door open
BD10	0.122	107	10	Flame Only	same as nine but igniter on 10s after door opened
BD11	0.122	107	10	Smoke Ball	repeat of BD10
BD12	0.177	123	0	Smoke Ball	igniter on when door opened
BD13	0.163	119	0	Smoke Ball	same as 12, igniter on 5 sec before door opened
BD14	0.184	121	0	Fire Ball	same as 12, no igniter
BD15	0.183	120	0	Flame Only	same as 12, no igniter,flaming inside before door opened, new hinges 1/2" gap in corner
BD16	0.183	122	0	Flame Only	same as 12, no igniter,flaming inside before door opened, new hinges 1/2" gap in corner
BD17	0.165	121	0	Fire Ball	same as 12, no igniter, gasket on door
BD18	0.169	123	0	Flame Only	same as 12, no igniter
BD19	0.173	122	0	Smoke Ball	same as 12, no igniter
BD20	0.175	121	0	Flame Only	same as 12, no igniter
BD21	0.158	122	0	Fire Ball	same as 12, igniter on when door opened
BD22	0.168	123	0	Flame Only	same as 12, igniter on when door opened
BD23	0.169	123	0	Flame Only	same as 12, igniter on when door opened
BD24	0.176	121	0	Flame Only	same as 12, igniter on 10s after door opened
BD25	0.173	138	3	Fire Ball	same as 12, except delay, no igniter
BD26	0.180	119	0	Fire Ball	same as 12, no igniter, weak, *
BD27	0.182	121	0	Fire Ball	same as 12, no igniter, weak, *

Table 2. Summary of Series 2A Test Scenarios (continued)

Test	Fuel Mass Fraction	Time (sec) Door was Closed	Time (sec) b/n securing fuel and door open	Outcome	Comments
BD28	0.169	126	0	Fire Ball	same as 12, no igniter
BD29	0.219	120	0	Fire Ball	
BD30	0.225	121	0	Smoke Ball	same as 29
BD31	0.223	116	0	Fire Ball	same as 29
BD32	0.122	99	0	Fire Ball	
BD33	0.127	101	0	Fire Ball	same as 32, door reopened during closure procedure
BD34	0.128	98	0	Flame Only	same as 32, flaming at door during secondary fuel injection
BD35	0.173	293	173	Flame Only	
BD36	0.180	239	121	Fire Ball	same as 35 except delay
BD37	0.177	241	121	Fire Ball	same as 35 except delay, weak, *
BD38	0.178	240	121	Fire Ball	same as 35 except delay
BD39	0.161	241	119	Flame Only	same as 35, Door cracked open twice b/n closing + 2nd fuel injection
BD40	0.171	241	120	Fire Ball	same as 35, Door cracked open twice b/n closing + 2nd fuel injection, #
BD41	0.175	239	119	Fire Ball	same as 35
BD42	0.174	239	120	Fire Ball	same as 35, torch ignited gases only at door cracks, ext. with water before door opened, moderate, #
BD43	0.172	240	120	Fire Ball	same as 35, moderate, very slight press pulse, #
BD44	0.181	181	61	Fire Ball	vertical flame than fire ball
BD45	0.183	180	60	Fire Ball	same as 44, vertical flame than fire ball
BD46	0.181	181	62	Fire Ball	same as 44
BD47	0.184	181	61	Fire Ball	same as 44, #
BD48	0.182	181	61	Fire Ball	same as 44, #
BD49	0.182	181	62	Fire Ball	same as 44, vertical flame than fire ball
BD50	0.184	180	61	Fire Ball	same as 44, weak, *
BD51	0.186	182	68	Fire Ball	same as 44, burst of water with 4' applicator 30s before door opened, #

Table 2. Summary of Series 2A Test Scenarios (continued)

Test	Fuel Mass Fraction	Time (sec) Door was Closed	Time (sec) b/n securing fuel and door open	Outcome	Comments
BD52	0.178	182	61	Fire Ball	same as 44, ~2s burst of water, weak, *
BD53		185	61	Flame Only	same as 44, secondary fuel ran out, fuel mass fraction unknown
BD54	0.181	182	61	Fire Ball	same as 44
BD55	0.143	200	81	Nothing	same as 44, 3 bursts of water, 130s, 175s, 188s after door closed

* Weak fire ball

Very weak pressure pulse, with flame out the door

gases in the space consist solely of the products of stoichiometric combustion. An assumed initial gas constant for the total gas mixture is used to calculate a density for the mixture, this density is used to calculate a mass fraction, and this mass fraction along with the assumed composition of the non-fuel mixture is then used to calculate a new mixture gas constant. This procedure is repeated until the difference between the old and new values of the mixture gas constant converge to less than 0.01 J/kg K (approximately 0.5 percent).

Fig. 17 shows a bar graph of the nominal fuel mass fraction for each test along with notes designating pertinent differences between tests. Nominal fuel mass fractions ranged from 0.05 to 0.23. Based on this data there was not a distinct fuel mass fraction above which a well-defined and reproducible backdraft explosion (i.e., with fire ball) occurred. Backdrafts with strong, distinct fire balls occurred only about 50 percent of the time for similar test scenarios under repeat conditions. It was observed that winds of 8-16 km/hr had a strong effect on the test results (i.e., backdrafts were difficult to create). This effect can be seen in Fig. 17 which denotes the tests conducted under extremely windy conditions. The other tests were conducted under wind conditions of less than 6 km/hr. The winds blew from the west/northwest straight at the compartment door (Fig. 2). Visually, this appeared to retard the flow of hot gases out of the compartment and create a more turbulent bidirectional flow pattern at the door opening.

Tables 3 and 4 present the average temperature and oxygen concentration data as well as the estimated flame/fire ball size data for each test of Series 2A. Test data have been averaged over two different time periods each of which is 10 seconds in duration. The first time period is denoted as T1 and represents the time just prior to the fire door being closed. The second time period, denoted as T2, is a 10 second interval just prior to the door being opened to induce the backdraft. Period T2 is of most interest as it represents the conditions from which the backdraft phenomenon occurs or does not occur. This is the time period at which the nominal fuel mass fraction is calculated.

The oxygen concentration measurements have been adjusted to account for a 90 percent response time of the gas analysis system. Since opening the fire door and the ensuing gravity current occur on a time scale of about 15 seconds compared to the 60 second response time of the gas analysis system, the oxygen concentration measurements are unable to fully capture the relatively fast change in conditions. As a result, the oxygen concentrations reported at time T2 may appear artificially high for some tests. In cases where the tabulated data may be uncertain, the correct magnitude can be obtained from the plots as the lowest value just prior to the time that the door was opened.

An attempt was made to estimate the size of flame extension and/or fire balls exiting the test compartment during the backdraft events of Series 2A tests. Dimensions were obtained from visual observation and video by comparing the size of the flame/fire ball to the size of the test compartment.

At the time the door was opened, average compartment temperatures were typically 400 to 500°C and average oxygen concentrations were 1 to 2 percent. The largest fire balls observed were about 5 m (16 ft) in diameter and extended up to 8 m (26 ft) from the compartment. There was usually a 5 to 15 second delay between the time the door was opened and the sudden formation of the fire ball outside of the doorway.

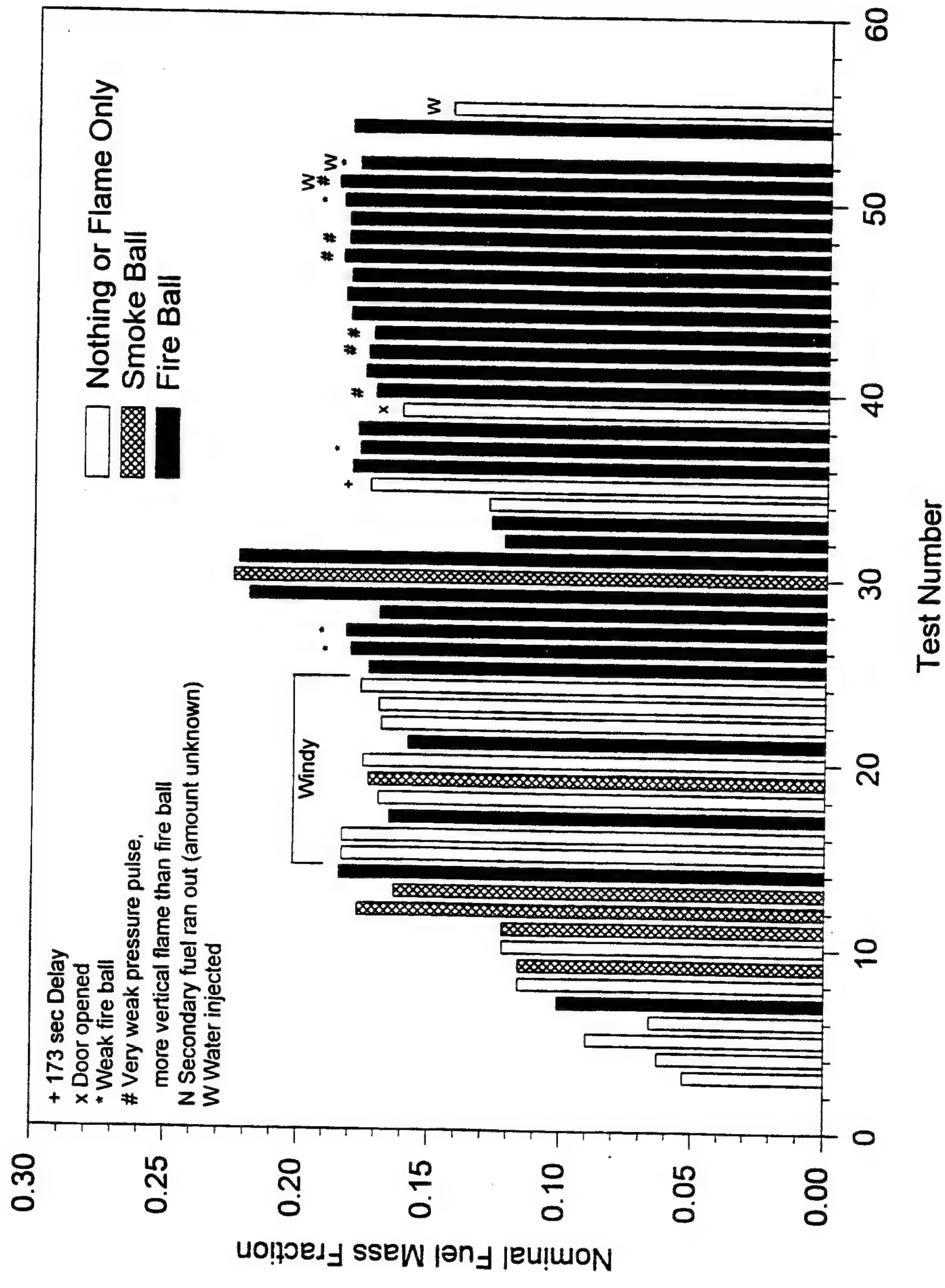

Fig. 17 Bar graph of nominal fuel mass fractions for series 2A tests

Table 3. Average temperature and oxygen concentration measurements for Series 2A tests

Test	Fuel Mass Fraction	Fuel				Temperatures (C)				Oxygen (mole fraction-dry)			
		Volume		Mass		At T1		At T2		At T1		At T2	
		(gal)	(l)	(kg)	(lb)	Gas	Bulkhead	Gas	Bulkhead	O_2 High	$O_2$0 Low	O_2 High	O_2 Low
BD1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
BD2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
BD3	0.053	0.25	0.96	0.78	1.71	678	481	449	450	0.011	0.114	0.014	0.079
BD4	0.063	0.31	1.19	0.96	2.13	621	465	427	282	0.000	0.084	0.007	0.041
BD5	0.090	0.48	1.80	1.46	3.22	651	70	407	52	0.000	0.091	0.010	0.043
BD6	0.066	0.31	1.19	0.96	2.13	737	81	464	79	0.035	0.109	0.013	0.064
BD7	0.101	0.48	1.80	1.46	3.22	770	61	493	49	0.026	0.109	0.009	0.075
BD8	0.116	0.59	2.22	1.80	3.96	768	541	452	484	0.031	0.101	0.059	0.072
BD9	0.116	0.56	2.12	1.74	3.84	780	513	476	480	0.018	0.109	0.023	0.079
BD10	0.122	0.56	2.12	1.74	3.84	818	531	521	500	0.016	0.116	0.011	0.085
BD11	0.122	0.56	2.12	1.74	3.84	800	505	521	482	0.013	0.120	0.044	0.092
BD12	0.177	0.93	3.52	2.89	6.38	784	491	454	455	0.045	0.125	0.002	0.056
BD13	0.163	0.93	3.52	2.89	6.38	740	503	387	425	0.001	0.105	0.005	0.054
BD14	0.184	0.93	3.52	2.89	6.38	789	506	484	473	0.014	0.100	0.001	0.067
BD15	0.183	0.93	3.52	2.89	6.38	799	495	482	459	0.031	0.118	0.001	0.013
BD16	0.183	0.93	3.52	2.89	6.38	772	488	481	454	-0.002	0.104	0.000	0.014
BD17	0.165	0.93	3.52	2.89	6.38	766	355	395	334	0.021	0.115	0.002	0.035
BD18	0.169	0.93	3.52	2.89	6.38	719	407	417	380	0.004	0.083	0.008	0.020
BD19	0.173	0.93	3.52	2.89	6.38	819	419	435	391	0.035	0.107	0.007	0.017
BD20	0.175	0.93	3.52	2.89	6.38	849	458	443	419	0.011	0.088	0.001	0.031
BD21	0.158	0.93	3.52	2.89	6.38	849	465	364	383	0.008	0.084	0.000	0.036
BD22	0.168	0.93	3.52	2.89	6.38	871	464	409	318	0.005	0.094	0.000	0.033
BD23	0.169	0.93	3.52	2.89	6.38	819	475	416	374	0.008	0.087	0.000	0.040
BD24	0.176	0.93	3.52	2.89	6.38	729	375	447	358	0.000	0.073	0.003	0.042
BD25	0.173	0.93	3.52	2.89	6.38	869	441	436	411	0.004	0.075	0.000	0.053
BD26	0.180	0.93	3.52	2.89	6.38	796	453	466	422	0.002	0.061	0.000	0.046
BD27	0.182	0.93	3.52	2.89	6.38	907	465	477	430	0.009	0.044	0.000	0.045
BD28	0.169	0.93	3.52	2.89	6.38	810	399	416	380	0.011	0.087	0.003	0.070

Table 3. Average temperature and oxygen concentration measurements for Series 2A tests (continued)

Test	Fuel Mass Fraction	Fuel				Temperatures (C)				Oxygen (mole fraction-dry)			
		Volume		Mass		At T1		At T2		At T1		At T2	
		(gal)	(l)	(kg)	(lb)	Gas	Bulkhead	Gas	Bulkhead	O_2 High	O_20 Low	O_2 High	O_2 Low
BD29	0.219	1.22	4.62	3.80	8.37	793	436	440	411	0.007	0.087	0.001	0.073
BD30	0.225	1.22	4.62	3.80	8.37	847	466	463	432	0.001	0.077	0.000	0.059
BD31	0.223	1.22	4.62	3.80	8.37	815	432	455	404	0.003	0.069	0.001	0.063
BD32	0.122	0.61	2.31	1.90	4.18	698	446	454	422	0.010	0.102	0.001	0.046
BD33	0.127	0.61	2.31	1.90	4.18	725	474	485	447	0.011	0.093	0.001	0.080
BD34	0.128	0.61	2.31	1.90	4.18	735	465	495	441	0.005	0.062	0.007	0.075
BD35	0.173	0.93	3.52	2.89	6.38	850	412	433	371	0.006	0.077	0.008	0.114
BD36	0.180	0.93	3.52	2.89	6.38	904	441	465	396	0.007	0.085	0.007	0.094
BD37	0.177	0.93	3.52	2.89	6.38	865	426	455	384	0.005	0.086	0.008	0.090
BD38	0.178	0.93	3.52	2.89	6.38	880	423	458	381	0.007	0.074	0.005	0.079
BD39	0.161	0.93	3.52	2.89	6.38	870	308	379	291	0.005	0.095	0.014	0.125
BD40	0.171	0.93	3.52	2.89	6.38	854	379	423	346	0.004	0.056	0.003	0.125
BD41	0.175	0.93	3.52	2.89	6.38	886	408	443	369	0.008	0.067	0.022	0.090
BD42	0.174	0.93	3.52	2.89	6.38	874	404	439	363	0.003	0.060	0.007	0.080
BD43	0.172	0.93	3.52	2.89	6.38	886	388	429	349	0.002	0.052	0.009	0.110
BD44	0.181	0.93	3.52	2.89	6.38	932	387	471	357	0.001	0.074	0.002	0.040
BD45	0.183	0.93	3.52	2.89	6.38	941	407	479	370	0.003	0.076	0.019	0.013
BD46	0.181	0.93	3.52	2.89	6.38	912	401	474	365	0.003	0.035	0.014	0.070
BD47	0.184	0.93	3.52	2.89	6.38	941	407	484	370	0.003	0.039	0.003	0.039
BD48	0.182	0.93	3.52	2.89	6.38	904	396	479	363	0.001	0.044	0.004	0.042
BD49	0.182	0.93	3.52	2.89	6.38	957	371	479	341	0.001	0.061	0.019	0.055
BD50	0.184	0.93	3.52	2.89	6.38	943	392	485	358	0.001	0.040	0.006	0.040
BD51	0.186	0.93	3.52	2.89	6.38	962	409	498	372	0.004	0.058	0.003	0.037
BD52	0.178	0.93	3.52	2.89	6.38	962	404	459	367	0.004	0.081	0.010	0.051

Table 3. Average temperature and oxygen concentration measurements for Series 2A tests (continued)

Test	Fuel Mass Fraction	Fuel				Temperatures (C)				Oxygen (mole fraction-dry)			
		Volume		Mass		At T1		At T2		At T1		At T2	
		(gal)	(l)	(kg)	(lb)	Gas	Bulkhead	Gas	Bulkhead	O_2 High	O_20 Low	O_2 High	O_2 Low
BD53		?	?	?	NA	947	412	312	368	0.004	0.058	0.099	0.129
BD54	0.181	0.93	3.52	2.89	6.38	876	397	473	376	0.001	0.058	0.000	0.033
BD55	0.143	0.93	3.52	2.89	6.38	870	397	296	367	0.000	0.100	0.058	0.044

* Weak fire ball

Very weak pressure pulse, with flame out the door

Table 4. Estimated size of flame extension and/or fire balls exiting the test compartment during the backdraft events of Series 2B tests

Test	Fuel Mass Fraction	Time (sec) b/n opening door and			Flame Size				Fire Ball Size			
		Flame	Smoke Ball	Fire Ball	Extension		Height		Width		Extension	
					(ft)	(m)	(ft)	(m)	(ft)	(m)	(ft)	(m)
BD1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
BD2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
BD3	0.053											
BD4	0.063											
BD5	0.090											
BD6	0.066	21			0.7	0.2	1.5	0.4				
BD7	0.101			9					13.2	4.0	9.7	3.0
BD8	0.116											
BD9	0.116	7	6		0.7	0.2	1.5	0.4				
BD10	0.122	0			2.9	0.9	8.5	2.6				
BD11	0.122	7	5		5.1	1.6	9.6	2.9				
BD12	0.177	14	12		5.1	1.6	7.4	2.2				
BD13	0.163	8	5		4.0	1.2	8.8	2.7				
BD14	0.184			8					12.2	3.7	13.2	4.0
BD15	0.183	1			3.3	1.0	8.3	2.5				
BD16	0.183	1			3.9	1.2	12.7	3.9				
BD17	0.165			19					12.2	3.7	12.1	3.7
BD18	0.169	19			5.5	1.7	6.6	2.0				
BD19	0.173	13	10		1.1	0.3	4.4	1.3				
BD20	0.175	17			1.9	0.6	3.8	1.2				
BD21	0.158		4	5					14.0	4.3	14.7	4.5
BD22	0.168	9			7.7	2.3	9.0	2.7				
BD23	0.169	9										
BD24	0.176	14										
BD25	0.173	15		16					16.0	4.9	18.6	5.7
BD26	0.180			15					8.5	2.6	11.5	3.5
BD27	0.182			4					8.5	2.6	10.9	3.3

Table 4. Estimated size of flame extension and/or fire balls exiting the test compartment during the backdraft events of Series 2B tests (continued)

Test	Fuel Mass Fraction	Time (sec) b/n opening door and			Flame Size				Fire Ball Size			
		Flame	Smoke Ball	Fire Ball	Extension		Height		Width		Extension	
					(ft)	(m)	(ft)	(m)	(ft)	(m)	(ft)	(m)
BD28	0.169	7		9					14.0	4.3	24.8	7.5
BD32	0.122	7		8					13.2	4.0	12.7	3.9
BD33	0.127			7					12.0	3.7	11.3	3.4
BD34	0.128	2			6.6	2.0	8.8	2.7				
BD35	0.173	12			6.1	1.8	9.9	3.0				
BD36	0.180			12					16.0	4.9	16.6	5.0
BD37	0.177	5		14					8.5	2.6	10.5	3.2
BD38	0.178		12	13					17.4	5.3	23.2	7.1
BD39	0.161	42			5.2	1.6	6.6	2.0				
BD40	0.171	16		18					6.0	1.8	13.2	4.0
BD41	0.175		13	14					18.0	5.5	26.5	8.1
BD42	0.174	12		13					8.5	2.6	12.1	3.7
BD43	0.172	14		16					8.5	2.6	11.6	3.5
BD44	0.181	5		7					14.0	4.3	24.3	7.4
BD45	0.183	5		7					15.0	4.6	25.4	7.7
BD46	0.181			10					16.0	4.9	25.4	7.7
BD47	0.184	3		5					7.9	2.4	8.8	2.7
BD48	0.182	5		6					8.5	2.6	9.9	3.0
BD49	0.182	3		4					13.0	4.0	16.6	5.0
BD50	0.184	3		5					8.5	2.6	15.3	4.7
BD51	0.186			4					9.0	2.7	9.0	2.8
BD52	0.178	2		4					7.9	2.4	12.5	3.8
BD53												
BD54	0.181	6		7					12.0	3.7	11.8	3.6
BD55	0.143											

The Series 2A tests were successful in (1) developing a safe method for producing backdrafts while avoiding dangerously explosive mixtures in the compartment, (2) demonstrating that compartment temperatures were sufficient for igniting diesel vapor/aerosol, and (3) providing preliminary results that water injection is a feasible method for mitigating backdrafts.

6.2 Series 2B

Table 5 shows a summary of the test scenarios conducted. Series 2B tests focused on extending the Series 2A work to develop a well-defined, reproducible backdraft test. In addition, the effectiveness of water spray injection as a mitigating tactic was studied. It was believed that the creation of conditions with higher nominal fuel mass fractions (i.e., greater than 0.18 which was typical for most of Series 2A tests) would lead to a reproducible test. At higher fuel concentrations, the effect of the difficult to control variables, such as wind and leakage around the warping door frame, would be minimized.

Table 3 shows a summary of the Series 2B test scenarios conducted. This Table lists the test number, the nominal fuel mass fraction, the amount of water injected (if any), the total time the door was closed, the delay time between securing the secondary fuel and opening the door, the resulting outcome, and general comments. The bold division lines group tests which were essentially repeat tests of the same scenario. The resulting outcome describes what happened outside of the door. In some cases, there was a deflagration in the compartment (noted by a peak rise in temperature and pressure) without a fire ball outside of the compartment. These tests were characterized by a roll out of flame under the soffit or the formation of a large ball of smoke.

Fig. 18 shows a bar graph of the nominal fuel mass fraction for each test along with notes designating pertinent differences between tests. Nominal fuel mass fractions ranged from 0.13 to 0.29. The majority of tests were conducted with nominal fuel mass fractions of about 0.25 (i.e., 4.9 kg (1.6 gal) of secondary fuel). As can be seen in Table 3 and Fig. 18 (tests BD74 to BD115), a reproducible test scenario that resulted in a strong backdraft explosion was developed. This was achieved after it was found that a build up of soot on the walls of the compartment had a dramatic effect on creating a backdraft explosion. As can be seen in Fig. 18, prior to test BD74 less than 60 percent of the tests resulted in well-defined explosions with fire balls outside of the compartment. This occured despite fuel mass fractions as high as 0.29. Prior to test BD74 the compartment walls were covered with soot, up to 1.9 cm thick. It is believed that the soot (carbon) buildup on the interior surfaces absorbed some of the fuel injected into the compartment. Therefore, there was a reduction in the amount of vaporized fuel in the space such that the fuel mass fraction (which assumes all chemical species in the gas phase) was actually lower than calculated. Dependent on the mass of soot buildup, enough fuel was adsorbed in some cases to prevent a bakdraft from occurring. By cleaning the soot from the test compartment walls every 10 tests the effect of the soot was minimized (soot layers were less than 2 mm thick). As a result, the same test conditions resulted in reproducible backdraft explosions with strong, distinct fire balls for 22 out of 22 tests. The effect of the soot buildup appeared to be a larger factor than the wind conditions of Series 2A; however, this can not be fully substantiated as the same high wind conditions did not occur during this series. Weather conditions for Series 2B were very still with wind speeds typically less than 4.8 km/hr (3 mph).

The data presented in Fig. 18 shows that fuel mass fractions of 0.17 or greater are necessary to produce a backdraft explosion. This is particularly demonstrated by the results of tests BD103 through BD113. For example, tests BD 106, 109, and 110 had fuel mass fractions

Table 5. Summary of Series 2B Test Scenarios

Test	Fuel Mass Fraction	Water Injected (kg)	Water Used (l)	Water Used (gal)	Time (sec) Door was Closed	Time (sec) b/n securing fuel and door open	Outcome	Comments
BD56	0.25				241	120	Fire Ball	
BD57	0.26				240	120	Fire Ball	Repeat BD56
BD58	0.25				262	122	Smoke Ball	Repeat BD56
BD59	0.26				243	123	Fire Ball	Repeat BD56
BD60	0.26				243	122	Flame	Repeat BD56, several weak pressure pulses
BD61	0.26				240	123	Smoke Ball	Repeat BD56, slight presssure pulse before flame
BD62	0.26				241	121	Fire Ball	Repeat BD56, large smoke ball before fireball
BD63	0.26				242	120	Smoke Ball	Repeat BD56
BD64	0.28				280	136	Fire Ball	
BD65	0.29				249	121	Fire Ball	70 s injection time
BD66	0.29				253	122	Smoke Ball	Repeat BD65, Several mild pulses (smoke ball) then flame
BD67	0.29				252	122	Fire Ball	Repeat BD65, smoke ball before fire ball *
BD68	0.29				253	220	Fire Ball	Repeat BD65, *
BD69	0.29				252	123	Smoke Ball	Repeat BD65, smoke ball then flame
BD70	0.26				241	122	Fire Ball	Repeat BD56

Table 5. Summary of Series 2B Test Scenarios (continued)

Test	Fuel Mass Fraction	Water Injected (kg)	Water Used (l)	Water Used (gal)	Time (sec) Door was Closed	Time (sec) b/n securing fuel and door open	Outcome	Comments
BD71	0.26				243	121	Fire Ball	Repeat BD56, #
BD72	0.26				240	121	Fire Ball	Repeat BD56, almost immediate flame, #
BD73	0.26				253	121	Fire Ball	Repeat BD56, mild ball after initial flame out
BD74	0.25				241	121	Fire Ball	Repeat BD56, soot cleaned out of compartment
BD75	0.25				239	120	Fire Ball	Repeat BD56
BD76	0.26				243	123	Fire Ball	Repeat BD56
BD77	0.26				242	122	Fire Ball	Repeat BD56
BD78	0.26				242	121	Fire Ball	Repeat BD56
BD79	0.26				239	120	Fire Ball	Repeat BD56
BD80	0.25				245	124	Fire Ball	Repeat BD56
BD81	0.25				241	122	Fire Ball	Repeat BD56
BD82	0.25				242	122	Fire Ball	Repeat BD56
BD83	0.25				241	121	Fire Ball	Repeat BD56
BD84	0.24				241	122	Fire Ball	Repeat BD56
BD85	0.25				241	121	Fire Ball	Repeat BD56
BD86	0.25				251	122	Fire Ball	Repeat BD56
BD87	0.25				241	121	Fire Ball	Repeat BD56

Table 5. Summary of Series 2B Test Scenarios (continued)

Test	Fuel Mass Fraction	Water Injected (kg)	Water Used (l)	Water Used (gal)	Time (sec) Door was Closed	Time (sec) b/n securing fuel and door open	Outcome	Comments
BD88	0.25				242	122	Fire Ball	Repeat BD56
BD89	0.16	10.945	10.978	2.9	241	122	Fire Ball	Repeat BD56, w/ water spray, *
BD90	0.16	10.9	10.98	2.9	242	123	Fire Ball	Repeat BD56, w/ water spray, *
BD91	0.22				242	132	Fire Ball	Repeat BD90, w/out water, 0.27 mass fraction
BD92	0.16	13.7	13.74	3.63	242	92		Repeat BD87, very slight pulse, long delay
BD93	0.14	13.7	13.74	3.63	242	123		Repeat BD56, w/ water spray, minimal soot on walls
BD94	0.24				241	121	Fire Ball	Repeat BD56
BD95	0.14	13.7	13.74	3.63	242	122		Repeat BD56, w/ water spray
BD96	0.15	10.9	10.98	2.9	243	123		Repeat BD56, w/ water spray
BD97	0.24				241	121	Fire Ball	Repeat BD56
BD98	0.17	8.2	8.21	2.17	242	121	Fire Ball	Repeat BD56, w/ water spray, *
BD99	0.17	8.2	8.21	2.17	242	121	Fire Ball	Repeat BD56, w/ water spray, *
BD100	0.19	5.5	5.49	1.45	242	121	Fire Ball	Repeat BD56, w/ water spray, *
BD101	0.25				243	122	Fire Ball	Repeat BD56
BD102	0.14	13.7	13.74	3.63	241	121		Repeat BD56, w/ water spray, *
BD103	0.25				241	121	Fire Ball	
BD104	0.21				242	128	Fire Ball	

Table 5. Summary of Series 2B Test Scenarios (continued)

Test	Fuel Mass Fraction	Water Injected (kg)	Water Used (l)	Water Used (gal)	Time (sec) Door was Closed	Time (sec) b/n securing fuel and door open	Outcome	Comments
BD105	0.17				241	121	Fire Ball	
BD106	0.14				242	151		no flame, no ball
BD107	0.26				241	121	Fire Ball	
BD108	0.17				241	120	Fire Ball	
BD109	0.14				242	122		Very mild, #
BD110	0.13				244	121		
BD111	0.25				241	120	Fire Ball	
BD112	0.25				242	122	Fire Ball	
BD113	0.17				241	118	Fire Ball	
BD114	0.16	10.9	10.98	2.90	241	121		Repeat BD96, #
BD115	0.26				240	117	Fire Ball	

* Weak fire ball

Very weak pressure pulse, with flame out the door

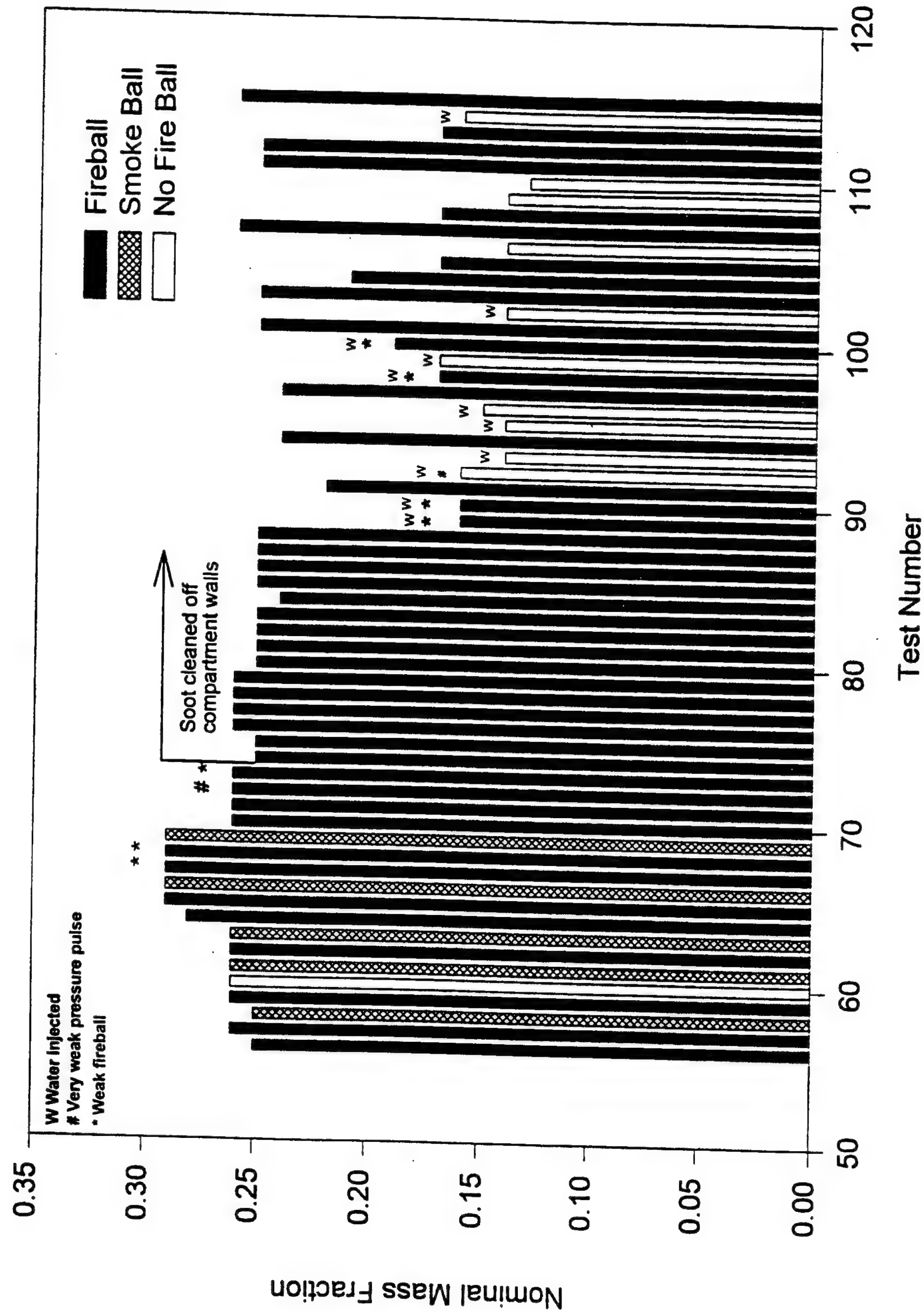

Fig. 18 Bar graph of nominal fuel mass fractions for series 2A tests

of 0.13 or 0.14 with no fire ball; tests BD 103-104, 107, 108, 111-113, and 115 had fuel mass fractions of 0.17 or higher, and all resulted in backdraft explosions with large fire balls. Procedurally, the tests were identical except for the amount of secondary fuel injected into the fire compartment. The tests that did not result in fire balls had average gas temperatures equal to or greater than the tests that did and oxygen concentrations were similar as well. Therefore, these results indicate that the fuel mass fraction was the determining factor for creating the explosion.

Fig. 18 also shows the effect of water injection into the fire space using the same backdraft test scenario. The fuel mass fractions are decreased due to the water vapor in the space. If water was not injected the fuel mass fraction would be the same (0.25) as in tests without water. Depending on the amount of water used, the tests with water injection resulted in either the elimination of the explosion (i.e., the fire ball) or in backdraft explosions of reduced intensity. This subject is addressed in more detail in the Discussion section.

Tables 6 and 7 present the average temperature and oxygen concentration data as well as the estimated flame/fire ball size data for each test of Series 2B. Test data have been averaged over two different time periods each of which is 10 seconds in duration. The first time period is denoted as T1 and represents the time just prior to the fire door being closed. The second time period, denoted as T2, is a 10 second interval just prior to the door being opened to induce the backdraft. Period T2 is of most interest as it represents the conditions from which the backdraft phenomenon occurs or does not occur. This is the time period at which the nominal fuel mass fraction is calculated.

The oxygen concentration measurements have been adjusted to account for a 90 percent response time of the gas analysis system. Since opening the fire door and the ensuing gravity current occur on a time scale of about 15 seconds compared to the 60 second response time of the gas analysis system, the oxygen concentration measurements are unable to fully capture the relatively fast change in conditions. As a result, the oxygen concentrations reported at time T2 may appear artificially high for some tests.

An attempt was made to estimate the size of flame extension and/or fire balls exiting the test compartment during the backdraft events of Series 2B tests. Dimensions were obtained from visual observation and video by comparing the size of the flame/fire ball to the size of the test compartment. For Series 2B, markers were positioned within the view of the video camera to assist in the measurement of how far the fire extended away from the fire door. Markers were placed every 5 ft from 5 to 30 ft away from the door.

At the time the door was opened, average compartment temperatures were typically 340 to 400°C, and average oxygen concentrations were 0.5 to 1.5 percent. These gas temperatures are 50 to 100°C lower than observed for Series 2A tests. The difference is attributed to the removal of the soot from inside the comparment. It is believed that in Series 2A tests the excessive buildup of soot in the compartment was absorbing some of the secondary fuel injected into the space. As a result there was a reduction in the amount of fuel vaporized, and thus, a reduction in the amount of heat absorbed from the compartment gases due to the heat of the vaporization of the fuel. In the Series 2B tests in which the compartment was clean of soot, gas temperatures would be lower since more fuel is vaporized, and consequently, more heat is extracted from the compartment gases. This trend is also supported by the temperature data of the Series 2B tests before and after soot was being cleaned from the compartment walls (i.e., before and after test BD74). The largest fire balls observed were about 7 m in diameter and extended over 9 m from the compartment. Similar to the Series 2A tests, there was usually a 15 to 20 second delay between the time the door was opened and the sudden formation of the

Table 6. Average temperature and oxygen concentration measurements for Series 2B tests

Test	Fuel Mass Fraction	Fuel				Water		Temperature (C)				Oxygen (mole fraction-dry)			
		Volume		Mass		Injected		At T1		At T2		At T1		At T2	
		(gal)	(l)	(kg)	(lb)	(kg)	(lb)	Gas	Bulkhead	Gas	Bulkhead	O_2 High	O_2 Low	O_2 High	O_2 Low
BD56	0.25	1.58	5.98	4.92	10.8				430	388	406	0.003	0.052	0.007	0.085
BD57	0.26	1.58	5.98	4.92	10.8				458	396	429	0.009	0.074	0.000	0.000
BD58	0.25	1.58	5.98	4.92	10.8				456	387	417	0.009	0.071	0.002	0.093
BD59	0.26	1.58	5.98	4.92	10.8				465	410	425	0.005	0.062	0.000	0.000
BD60	0.26	1.58	5.98	4.92	10.8				453	404	413	0.001	0.073	0.004	0.072
BD61	0.26	1.58	5.98	4.92	10.8										
BD62	0.26	1.58	5.98	4.92	10.8										
BD63	0.26	1.58	5.98	4.92	10.8				448	411	408	0.004	0.068	0.006	0.061
BD64	0.28	1.77	6.70	5.51	12.1				447	398	405	0.007	0.067	0.011	0.064
BD65	0.29	1.81	6.85	5.63	12.4				465	411	425	0.002	0.064	0.000	0.040
BD66	0.29	1.81	6.85	5.63	12.4				453	411	411	0.006	0.049	0.000	0.067
BD67	0.29	1.81	6.85	5.63	12.4				445	414	399	0.002	0.055	0.000	0.059
BD68	0.29	1.81	6.85	5.63	12.4				435	412	394	0.003	0.047	0.000	0.055
BD69	0.29	1.81	6.85	5.63	12.4				459	412	397	0.000	0.058	0.000	0.049
BD70	0.26	1.58	5.98	4.92	10.8				456	404	400	0.002	0.041	0.000	0.000
BD71	0.26	1.58	5.98	4.92	10.8				456	413	404	0.006	0.074	0.000	0.000
BD72	0.26	1.58	5.98	4.92	10.8				462	422	405	0.003	0.045	0.000	0.040

Table 6. Average temperature and oxygen concentration measurements for Series 2B tests (continued)

Test	Fuel Mass Fraction	Fuel				Water		Temperature (C)				Oxygen (mole fraction-dry)			
		Volume		Mass		Injected		At T1		At T2		At T1		At T2	
		(gal)	(l)	(kg)	(lb)	(kg)	(lb)	Gas	Bulkhead	Gas	Bulkhead	O_2 High	O_2 Low	O_2 High	O_2 Low
BD73	0.26	1.58	5.98	4.92	10.8				449	418	397	0.003	0.061	0.000	0.012
BD74	0.25	1.58	5.98	4.92	10.8				507	382	443	0.003	0.062	0.000	0.000
BD75	0.25	1.58	5.98	4.92	10.8				538	388	433	0.012	0.070	0.000	0.000
BD76	0.26	1.58	5.98	4.92	10.8				527	390	419	0.015	0.091	0.000	0.087
BD77	0.26	1.58	5.98	4.92	10.8				523	394	415	0.009	0.066	0.003	0.082
BD78	0.26	1.58	5.98	4.92	10.8				514	396	411	0.011	0.073	0.006	0.088
BD79	0.26	1.58	5.98	4.92	10.8				580	394	433	0.013	0.062	0.000	0.000
BD80	0.25	1.58	5.98	4.92	10.8				588	387	427	0.027	0.096	0.000	0.000
BD81	0.25	1.58	5.98	4.92	10.8				569	378	412	0.036	0.093	0.000	0.058
BD82	0.25	1.58	5.98	4.92	10.8				571	390	419	0.031	0.092	0.000	0.000
BD83	0.25	1.58	5.98	4.92	10.8				515	375	391	0.028	0.075	0.000	0.000
BD84	0.24	1.58	5.98	4.92	10.8				524	342	441	0.026	0.134	0.000	0.004
BD85	0.25	1.58	5.98	4.92	10.8				522	365	441	0.037	0.109	0.004	0.091
BD86	0.25	1.58	5.98	4.92	10.8				505	365	427	0.043	0.106	0.000	0.000
BD87	0.25	1.58	5.98	4.92	10.8				499	371	427	0.054	0.101	0.000	0.073
BD88	0.25	1.58	5.98	4.92	10.8				484	367	415	0.061	0.099	0.056	0.084
BD89	0.16	1.65	6.25	5.13	11.3	10.9	24.1		525	331	442	0.003	0.077	0.007	0.015
BD90	0.16	1.58	5.98	4.92	10.8	10.9	24.1		478	332	412	0.014	0.101	0.011	0.018
BD91	0.22	1.42	5.37	4.42	9.7				448	357	393	0.000	0.105	0.001	0.105
BD92	0.16	1.85	7.00	5.76	12.7	13.7	30.2		447	274	384	0.000	0.088	0.001	0.089
BD93	0.14	1.58	5.98	4.92	10.8	13.7	30.2		488	276	401	0.008	0.127	0.021	0.053

Table 6. Average temperature and oxygen concentration measurements for Series 2B tests (continued)

Test	Fuel Mass Fraction	Fuel				Water		Temperature (C)				Oxygen (mole fraction-dry)			
		Volume		Mass		Injected		At T1		At T2		At T1		At T2	
		(gal)	(l)	(kg)	(lb)	(kg)	(lb)	Gas	Bulkhead	Gas	Bulkhead	O_2 High	O_2 Low	O_2 High	O_2 Low
BD94	0.24	1.58	5.98	4.92	10.8				477	348	397	0.010	0.115	0.001	0.075
BD95	0.14	1.58	5.98	4.92	10.8	13.7	30.2		477	312	397	0.016	0.087	0.024	0.105
BD96	0.15	1.58	5.98	4.92	10.8	10.9	24.1		446	310	377	0.006	0.056	0.015	0.146
BD97	0.24	1.58	5.98	4.92	10.8				436	346	371	0.023	0.083	0.004	0.083
BD98	0.17	1.58	5.98	4.92	10.8	8.2	18.1		464	342	406	0.002	0.086	0.010	0.061
BD99	0.17	1.58	5.98	4.92	10.8	8.2	18.1		452	333	390	0.001	0.089	0.001	0.075
BD100	0.19	1.58	5.98	4.92	10.8	5.5	12.1		457	355	399	0.001	0.084	0.003	0.071
BD101	0.25	1.58	5.98	4.92	10.8				448	373	397	0.001	0.065	0.001	0.062
BD102	0.14	1.58	5.98	4.92	10.8	13.7	30.2		454	329	394	0.004	0.092	0.005	0.073
BD103	0.25	1.52	5.75	4.73	10.4				486	393	425	0.006	0.076	0.001	0.074
BD104	0.21	1.26	4.77	3.92	8.6				470	385	411	0.005	0.069	0.000	0.000
BD105	0.17	0.99	3.75	3.08	6.8				459	396	403	0.002	0.043	0.000	0.009
BD106	0.14	0.76	2.88	2.36	5.2				471	410	410	0.001	0.055	0.041	0.110
BD107	0.26	1.58	5.98	4.92	10.8				449	398	394	0.013	0.065	0.003	0.070
BD108	0.17	0.99	3.75	3.08	6.8				456	363	403	0.004	0.068	0.004	0.117
BD109	0.14	0.76	2.88	2.36	5.2				464	381	413	0.013	0.072	0.014	0.183
BD110	0.13	0.76	2.88	2.36	5.2				435	379	392	0.022	0.074	0.060	0.172
BD111	0.25	1.58	5.98	4.92	10.8				446	380	398	0.042	0.073	0.007	0.074
BD112	0.25	1.58	5.98	4.92	10.8				434	377	392	0.040	0.082	0.000	0.000
BD113	0.17	0.99	3.75	3.08	6.8				466	395	412	0.012	0.071	0.000	0.089
BD114	0.16	1.58	5.98	4.92	10.8	10.9	24.1		458	367	403	0.023	0.072	0.029	0.129

Table 6. Average temperature and oxygen concentration measurements for Series 2B tests (continued)

Test	Fuel Mass Fraction	Fuel				Water		Temperature (C)				Oxygen (mole fraction-dry)			
		Volume		Mass		Injected		At T1		At T2		At T1		At T2	
		(gal)	(l)	(kg)	(lb)	(kg)	(lb)	Gas	Bulkhead	Gas	Bulkhead	O_2 High	O_2 Low	O_2 High	O_2 Low
BD115	0.26	1.58	5.98	4.9158	10.8				459	395	406	0.018	0.077	0.003	0.067

Table 7. Estimated size of flame extension and/or fire balls exiting the test compartment during the backdraft events of Series 2B tests

Test	Fuel Mass Fraction	Time (sec) b/n opening door and			Size	Flame Size				Fire Ball Size			
		Flame	Smoke Ball	Fire Ball	Flame	Extension		Height		Width		Extension	
					Extension (ft)	(ft)	(m)	(ft)	(m)	(ft)	(m)	(ft)	(m)
BD56	0.254			17				14.0	4.3	28.5	8.7	22.0	6.7
BD57	0.257			16				17.5	5.3	28.3	8.6	17.5	5.3
BD58	0.254	22	20		6.0	6.0	1.8	6.5	2.0				
BD59	0.261			11				17.0	5.2	24.3	7.4	23.5	7.2
BD60	0.259	19			5.0	5.0	1.5	4.0	1.2				
BD61	0.260	19	17										
BD62	0.260		11	16				11.0	3.4	18.4	5.6	19.0	5.8
BD63	0.261	15	14		2.5	2.5	0.8	8.0	2.4				
BD64	0.281				19.5	19.5	5.9	16.0	4.9				
BD65	0.291			18				15.0	4.6	17.9	5.5	15.0	4.6
BD66	0.291	18	16		6.5	6.5	2.0	6.0	1.8				
BD67	0.292		15	16				12.0	3.7	5.5	1.7	10.5	3.2
BD68	0.291		17	19				9.0	2.7	11.7	3.6	11.0	3.4
BD69	0.291	20	17		6.1	6.1	1.9	5.5	1.7				
BD70	0.259			13				14.9	4.5	24.3	7.4	24.3	7.4
BD71	0.262			15				10.2	3.1	11.4	3.5	9.6	2.9
BD72	0.265			6				12.2	3.7	12.3	3.7	16.0	4.9
BD73	0.263			6				19.4	5.9	8.9	2.7	19.2	5.9
BD74	0.253			13				19.2	5.9	23.4	7.1	29.4	9.0
BD75	0.254			17				17.3	5.3	16.3	5.0	30.1	9.2

Table 7. Estimated size of flame extension and/or fire balls exiting the test compartment during the backdraft events of Series 2B tests (continued)

Test	Fuel Mass Fraction	Time (sec) b/n opening door and			Size	Flame Size				Fire Ball Size			
		Flame	Smoke Ball	Fire Ball	Flame	Extension		Height		Width		Extension	
					Extension (ft)	(ft)	(m)	(ft)	(m)	(ft)	(m)	(ft)	(m)
BD76	0.255	14		16				15.4	4.7	17.5	5.3	20.5	6.2
BD77	0.256	14		17				17.9	5.5	19.7	6.0	25.6	7.8
BD78	0.257			16				14.1	4.3	19.4	5.9	25.6	7.8
BD79	0.256			17				15.4	4.7	30.2	9.2	31.4	9.6
BD80	0.254			14				19.8	6.0	25.5	7.8	32.0	9.8
BD81	0.251				28.2	28.2	8.6	16.0	4.9				
BD82	0.255												
BD83	0.250												
BD84	0.240			23				15.1	4.6	20.8	6.3	24.0	7.3
BD85	0.247			18				16.2	4.9	32.0	9.8	24.5	7.5
BD86	0.247			17				17.4	5.3	20.5	6.2	23.5	7.2
BD87	0.249							13.6	4.1	17.6	5.4	22.6	6.9
BD88	0.248	20		22				10.8	3.3	21.8	6.6	22.6	6.9
BD89	0.161	30			11.3	11.3	3.4	8.0	2.4				
BD90	0.155			26				8.0	2.4	11.7	3.6	12.7	3.9
BD91	0.224			22				13.3	4.1	21.7	6.6	28.7	8.7
BD92	0.156			34				12.7	3.9	11.0	3.4	12.7	3.9
BD93	0.136									26.0	7.9		
BD94	0.242			21				13.3	4.1	11.0	3.4	32.0	9.8
BD95	0.140												

Table 7. Estimated size of flame extension and/or fire balls exiting the test compartment during the backdraft events of Series 2B tests (continued)

Test	Fuel Mass Fraction	Time (sec) b/n opening door and			Size	Flame Size				Fire Ball Size			
		Flame	Smoke Ball	Fire Ball	Flame	Extension		Height		Width		Extension	
					Extension (ft)	(ft)	(m)	(ft)	(m)	(ft)	(m)	(ft)	(m)
BD96	0.152												
BD97	0.241			21				19.3	5.9	28.0	8.5	26.7	8.1
BD98	0.171			33				12.7	3.9	7.3	2.2	12.0	3.7
BD99	0.170	32			8.0	8.0	2.4	12.7	3.9				
BD100	0.192	28		30				12.0	3.7	9.0	2.7	7.3	2.2
BD101	0.250			16				20.2	6.2	25.3	7.7	25.7	7.8
BD102	0.142												
BD103	0.248			15				18.1	5.5	21.3	6.5	25.0	7.6
BD104	0.211			17				10.4	3.2	27.7	8.4	25.0	7.6
BD105	0.174			15				18.1	5.5	16.3	5.0	20.5	6.2
BD106	0.141												
BD107	0.257			14				19.5	5.9	18.3	5.6	20.9	6.4
BD108	0.167			18				16.7	5.1	18.3	5.6	20.2	6.2
BD109	0.135	36						4.9	1.5			6.6	2.0
BD110	0.135												
BD111	0.252	14		15				10.4	3.2	19.1	5.8	9.7	3.0
BD112	0.251			13				17.4	5.3	33.7	10.3	26.4	8.0
BD113	0.174			11				18.9	5.8	27.1	8.3	21.6	6.6
BD114	0.160	25						7.0	2.1			4.2	1.3
BD115	0.256			12				18.1	5.5	22.6	6.9	21.7	6.6

fire ball outside of the doorway. In most instances, dense smoke obscured any view of the deflagration until it suddenly penetrated the door way. However, in some tests, the deflagration could be seen originating in the upper back (south-east) corner of the compartment and traveling as a flame across the overhead of the compartment. Contradictorily, for a few tests, the flame/fire ball appeared to originate low in the doorway.

The relative pressure across the compartment bulkhead was measured for Series 2B tests. The data were qualitatively similar between tests; however, they were not quantitatively reproducible with respect to the peak pressure during the backdraft. Fig. 19 shows a typical pressure time history for a test resulting in a fire ball (test BD86). During the preburn period (<336 s), there is a marginally negative pressure differential as measured on the 250 Pa pressure transducer (capable of overranging to 280 Pa). This negative pressure differential indicates the inward flow of air low in the fire compartment. At 336 seconds, the door to the fire compartment was closed resulting in a large fluctuation in pressure due to the last pulsations in the fire plume before it was extinguished. As the door was quickly closed, the compartment experiences a rapid positive pressure rise due to the hot expanding combustion gases. This pressure rise is immediately followed by a sharp negative spike resulting from the fire plumes last pulsation to draw air into the compartment before extinguishing. The negative pressure fluctuation was both visibly and audibly observed as the fire door was sucked closed. Between 406 to 466 seconds, the secondary fuel was injected. During this time period, there was an initial pressurization of the compartment due to the injection and vaporization of the secondary fuel. Thick white smoke (mixture of original combustion products and fuel vapor) leaked from around the fire door during the initial injection. This leakage stopped about half way through the fuel injection process as can be seen in Fig. 19 when the pressure differential approaches 0 Pa. A second ejection of smoke around the door gasket would occur immediately as the fuel flow was secured (i.e., corresponding to the pressure pulse which started at 466 s). During several tests, a propane torch was used as a pilot flame to determine if the fuel-rich gas mixture leaking from the compartment could be ignited. The gases could be ignited only at the door gasket. At a distance of only 0.15 m, the gases were to dilute to be flammable. For the test in Fig. 19, the door was opened at 587 s followed by a deflagration in the compartment and the formation of a fire ball at 604 seconds. The compartment pressure increase during this backdraft explosion was 143 Pa which was about half of the pressure rise that occurred when the door was opened. The maximum pressure for tests in which a backdraft explosion occurred ranged from 100 to over 280 Pa. In some instances, identical tests produced pressure results that spanned this range. One possible reason for the deviation in the data is the occurrence of varying degrees of soot clogging in the pressure port. However, this hypothesis is not fully consistent with the results.

6.3 Series 3, 4 and 5

6.3.1 General Results

Series 3 through Series 5 tests (SBD01 to SBD65) were conducted aboard the ex-USS SHADWELL in order to examine the effects of the additional confines of a ship on the development of Class B explosions. Table 8 shows a summary of the test scenarios conducted. This table lists the test number, the nominal fuel mass fraction, the resulting outcome, the ventilation setup, and general comments. The resulting outcome describes what happened outside of the door. In some cases, there was a deflagration in the compartment (noted by a peak rise in temperature and pressure) without a fire ball outside of the compartment. These tests were characterized by a roll out of flame under the soffit.

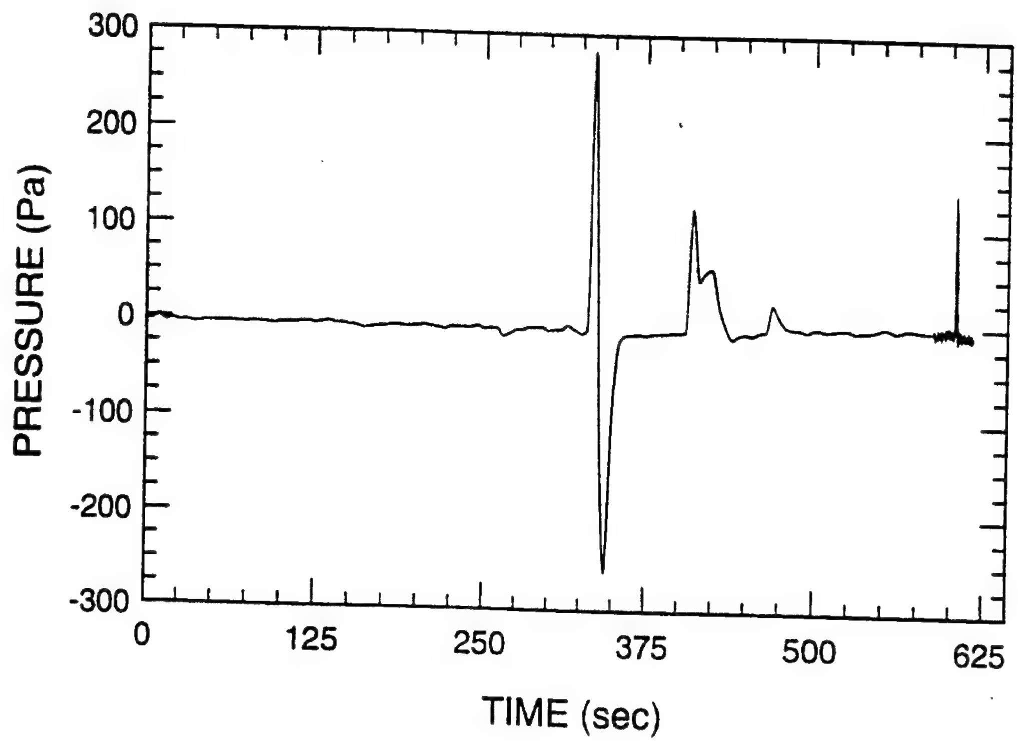

Fig. 19 - A typical pressure time history for a Series 2B backdraft test resulting in a fire ball (test BD86).

Table 8. Summary of series 3, 4 and 5 test scenarios conducted aboard the ex-USS SHADWELL

Test	Fuel Mass Fraction	Outcome	Ventilation	Comments
SBD01			full ventilation	2 MW Preburn Test
SBD02			full ventilation	2 MW Preburn Test
SBD03			full ventilation	2 MW Preburn Test -ABORTED
SBD04			full ventilation	2 MW Preburn Test - Compartment Cleaned
SBD05			full ventilation	2 MW Preburn Test
SBD06			full ventilation	1.5 MW Preburn Test -WTD 3-18-2 + 3-18-4 open to weather
SBD07			full ventilation	1.6 MW Preburn Test - ABORTED
SBD08			full ventilation	Same fuel settings as SBD07
SBD09	0.08		full ventilation	
SBD10	0.08		full ventilation	Same fuel settings as SBD09
SBD11			full ventilation	ABORTED
SBD12	0.09		full ventilation	
SBD13	0.11	Flame	full ventilation	Flame out the door with pressure wave
SBD14	0.11		full ventilation	
SBD15	0.13	Flame	full ventilation	Flame out the door with pressure wave
SBD16	0.13		full ventilation	IR camera inicated flamelet at nozzle after door was open
SBD17	0.14		full ventilation	IR camera inicated flamelet at nozzle after door was open
SBD18	0.16	Explosion	full ventilation	

Table 8. Summary of series 3, 4 and 5 test scenarios conducted aboard the ex-USS SHADWELL (continued)

Test	Fuel Mass Fraction	Outcome	Ventilation	Comments
SBD19	0.15		full ventilation	Same fuel settings as SBD08
SBD20	0.15		full ventilation	Same fuel settings as SBD18 - Compartment Cleaned
SBD21	0.17		full ventilation	
SBD22	0.17	Explosion	full ventilation	Compartment Cleaned and Resealed
SBD23	0.18	Explosion	full ventilation	1.6 then 1.9 MW preburn
SBD24	0.17	Explosion	full ventilation	
SBD25	0.17		full ventilation	1.4 then 1.7 MW preburn
SBD26	0.16		full ventilation	
SBD27	0.19	Explosion	full ventilation	Loudest sounding explosion, WTD 3-17-3 forced open
SBD28	0.19	Explosion	full ventilation	1.6 then 1.9 MW preburn for this test compartment cleaned
SBD29	0.18	Explosion	smoke curtains - fans at 100%	Same fuel settings as SBD28 , flame safety lamp blown out
SBD30	0.18	Explosion	smoke curtains - fans at 25%	Same fuel settings as SBD28 , flame safety lamp blown out
SBD31	0.18	Explosion	smoke curtains - fans secured	Same fuel settings as SBD28 , flame safety lamp blown out
SBD32	0.19	Explosion	full ventilation	Same fuel settings as SBD31 in procedure
SBD33	0.18	Explosion	full ventilation	Same fuel settings as SBD32 in procedure
SBD34				Aborted due to seal failure in pump room

Table 8. Summary of series 3, 4 and 5 test scenarios conducted aboard the ex-USS SHADWELL (continued)

Test	Fuel Mass Fraction	Outcome	Ventilation	Comments
SBD35	0.19	Explosion	smoke curtains - fans secured	Same fuel settings as SBD31 in procedure
SBD36			full ventilation	Buffer Zone #1, 2MW Preburn test
SBD37	0.13		full ventilation	Buffer Zone #1
SBD38	0.16	Explosion	full ventilation	Buffer Zone #1
SBD39	0.18	Explosion	full ventilation	Buffer Zone #1
SBD40	0.18	Explosion	smoke curtains - fans at 100%	Buffer Zone #1
SBD41	0.18	Explosion	smoke curtains - fans secured	Buffer Zone #1, E1-15-2 not in operation
SBD42	0.18	Explosion	boundaries open - fans secured	Buffer Zone #1, E1-15-2 not in operation
SBD43	0.18	Explosion	boundaries open - box fans	Buffer Zone #1, E1-15-2 not in operation
SBD44	0.18	Explosion	boundaries open - fans secured	Buffer Zone #1, Box Fan perpendicular to fire door, E1-15-2 not in operation for preburn
SBD45	0.18		smoke curtains - fans secured	Buffer Zone #1, a large leak developed at the top of the door
SBD46	0.19	Explosion	full ventilation	Buffer Zone #1
SBD47	0.14		full ventilation	Buffer Zone #1, water injection (2.4 gal)

Table 8. Summary of series 3, 4 and 5 test scenarios conducted aboard the ex-USS SHADWELL (continued)

Test	Fuel Mass Fraction	Outcome	Ventilation	Comments
SBD48	0.19	Explosion	smoke curtains - fans secured	Buffer Zone #1
SBD49	0.15		full ventilation	Buffer Zone #1, water injection (1.6 gal)
SBD50	0.17		full ventilation	Buffer Zone #2, temperatures were low in the fire space
SBD51	0.19	Flame	full ventilation	Buffer zone #2, E1-15-2 at 50% - E1-15-1 at 0%, immediate ignition outside of the fire door
SBD52	0.23		smoke curtains - fans secured	Buffer zone #2, E1-15-2 at 50% - E1-15-1 at 0%, fuel leakage from Pump Room to stbrd space b/n FR17 - 20
SBD53	0.20	Explosion	smoke curtains - fans secured	Buffer zone #2, D 3-18-0 open during preburn, E1-15-2 at 100% - E1-15-1 at 0%
SBD54	0.20		smoke curtains - fans secured	Buffer zone #2, repeat of SBD53
SBD55	0.20	Explosion	smoke curtains - fans secured	Modified buffer zone #1 (buffer zone #2 with D 3-18-0 open), no quad video, E1-15-2 at 100% -1 at 0%
SBD56	0.21	Explosion	smoke curtains - fans secured	Buffer zone #2, E1-15-2 at 100%, E1-15-1 at 0%
SBD57	0.19	Explosion	full ventilation	Buffer Zone #1
SBD58	0.14	Explosion	full ventilation	Buffer Zone #1, water injection (8.5kg, 2.25 gal), weak fire ball
SBD59	0.19	Explosion	smoke curtains - fans secured	Buffer Zone #1

Table 8. Summary of series 3, 4 and 5 test scenarios conducted aboard the ex-USS SHADWELL (continued)

Test	Fuel Mass Fraction	Outcome	Ventilation	Comments
SBD60	0.21	Explosion	smoke curtains - fans at 100 %	Buffer Zone #1
SBD61	0.19	Explosion	boundaries open - box fans	Buffer Zone #1
SBD62	0.20	Explosion	full ventilation	Buffer Zone #1
SBD63	0.19		full ventilation	Buffer Zone #1, water spray directed at door (95 gpm nozzle, 70 psi), fuel leakage around door
SBD64	0.14	Flame	full ventilation	Buffer Zone #1, water injection (9.8 kg, 2.6 gal), similar leakage to SBD63
SBD65	0.20	Explosion	full ventilation	Buffer Zone #1, weaker explosion than SBD 57 and 62 attributed to leakage

Nominal fuel mass fractions ranged from 0.08 to 0.23. Most tests were conducted at 0.18 or 0.19, which was sufficient to create a reproducible Class B explosion. These fuel mass fractions were typically achieved with 4.5 ℓ (1.2 gal) of diesel fuel (3.7 kg). Higher fuel mass fractions were not studied due to the uncertainty of possible damage from larger explosions.

As indicated in Table 8, there were several ventilation conditions tested. In a few cases, as noted in the comments, mechanical problems with the E1-15 fans prohibited the use of both fans. Nevertheless, full ventilation conditions were tested for all buffer zone configurations. Table 9 shows a comparison of the flow rates obtained for the main ventilation conditions studied. Buffer zone air changes per hour ranged from 82 to 709 for full ventilation conditions. The use of box fans in a desmoking setup produced 25 air changes per hour.

Table 9. Forced air flow rates for the buffer zone configurations studied

Buffer Zone	Size		Ventilation*		Flow Rate	Air Changes Per Hour
	m^3	ft^3	(m^3/s)	(cfm)		
EGR	191	6729	Full	4.3	9200	82
1	104	3657	Full	4.5	9600	157
1	104	3657	Fox Fans (Desmoking)	0.7	1500	25
2	20	715	Full	4	8500	709
2	20	715	E1-15-2 at 50%	1.85	3922	328

* Full ventilation consists of open boundaries and E1-15-1 and E1-15-2 fans at 100 percent

Several tests studied the effect of establishing a dead-air buffer zone on the backdraft explosion. Establishing a fully dead-air zone required shutting down the E1-15 fans and mechanically isolating the buffer zone. This was initially achieved through an incremental approach using Buffer Zone EGR (Fig. 4). The first test consisted of positioning smoke blankets and curtains over WTH 2-20-2 and WTD 3-17-1 and maintaining the fans at 100 percent capacity to clear out the second deck space. Subsequent tests consisted of setting the fans at 25 percent capacity and fully secured. Only with the fans fully secured was there no visible pressure differences across the hatch and door (i.e., curtains were not bulged to one side or the other).

Figs. 20-23 show the results for a representative test with a Class B explosion. The Figures show species concentrations within the fire compartment and temperature measurements both in the fire space and in the buffer zone. The test presented (SBD27) was conducted in Buffer Zone EGR with full ventilation (i.e., open boundaries and fans at 100 percent capacity). Figs. 20-21 show the CO, CO_2, and O_2 concentrations measured low and high in the fire compartment, respectively, as well as the fuel supply rate. As the preburn fire develops, the oxygen concentration decreases rapidly in the upper layer to undetectable levels (Fig. 21) and approaches about 11 percent near the deck (Fig. 20). In the upper layer CO concentrations exceed 3 percent which represent levels lethal within several breaths.

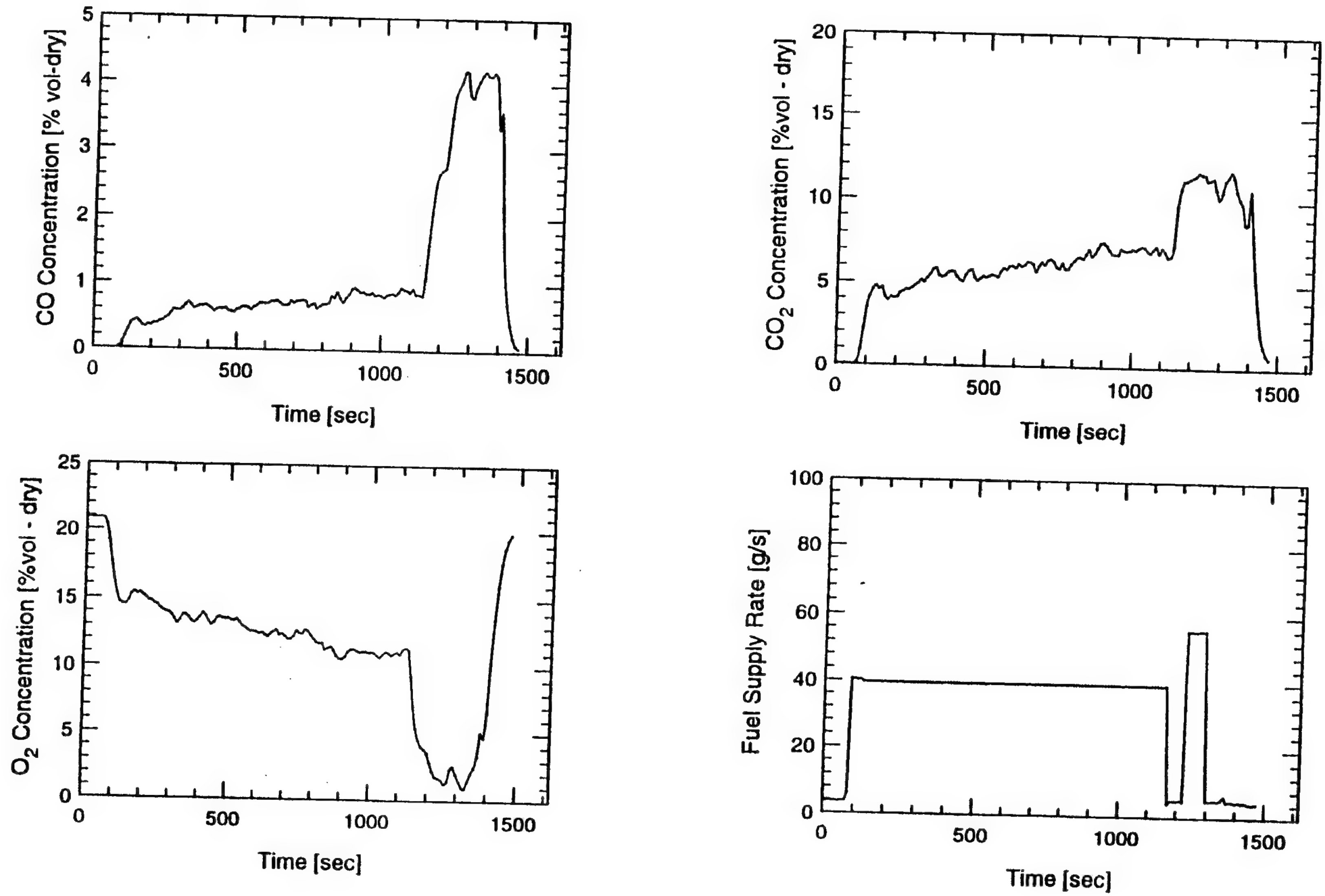

Fig. 20 - Typical CO, CO_2, and O_2 concentrations measured 0.3 m above deck in the fire compartment and the fuel supply rate for a backdraft test aboard the ex-USS SHADWELL (test SBD27).

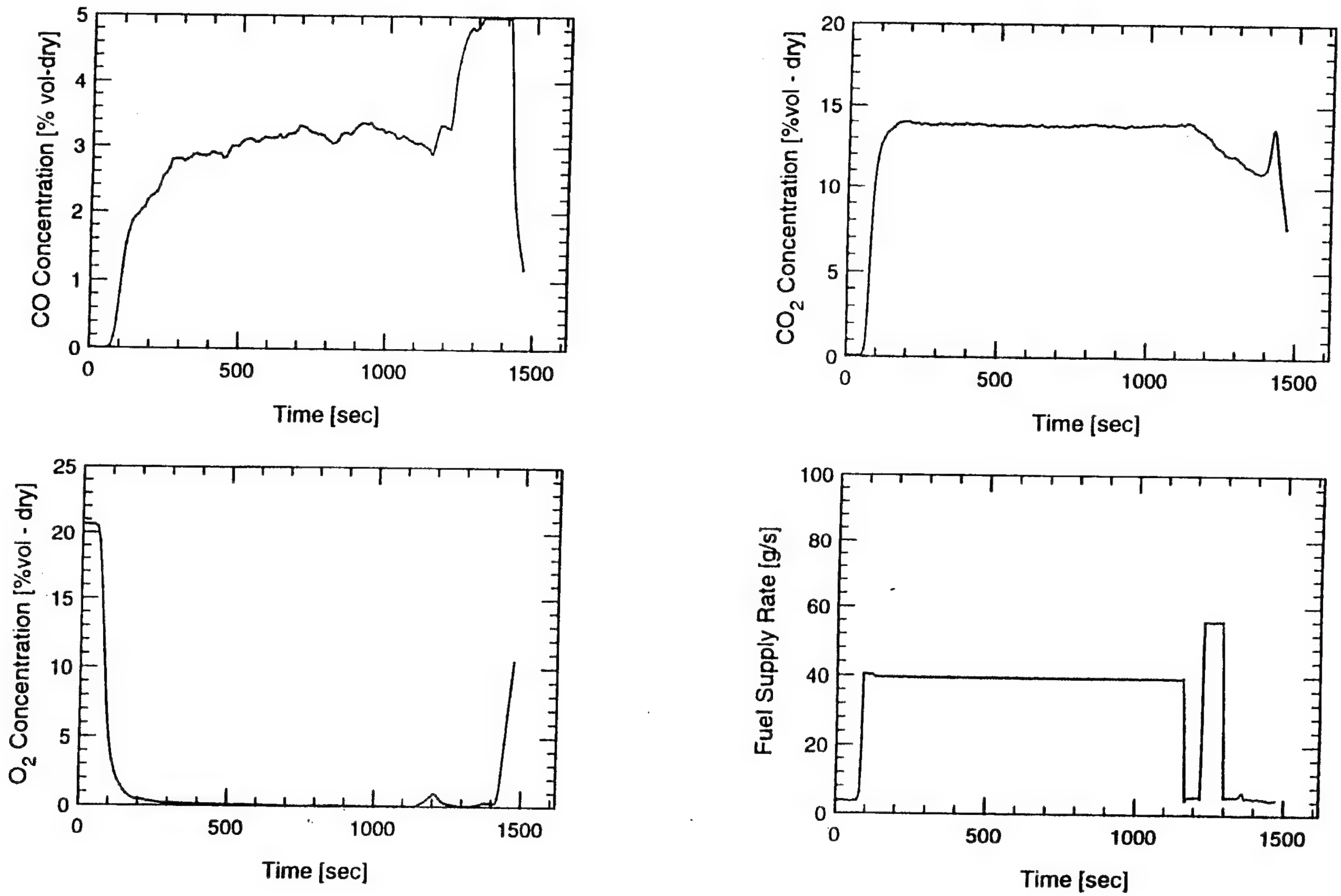

Fig. 21 - Typical CO, CO_2, and O_2 concentrations measured 2.8 m above the deck in the fire compartment and the fuel supply rate for a backdraft test aboard the ex-USS SHADWELL (test SBD27).

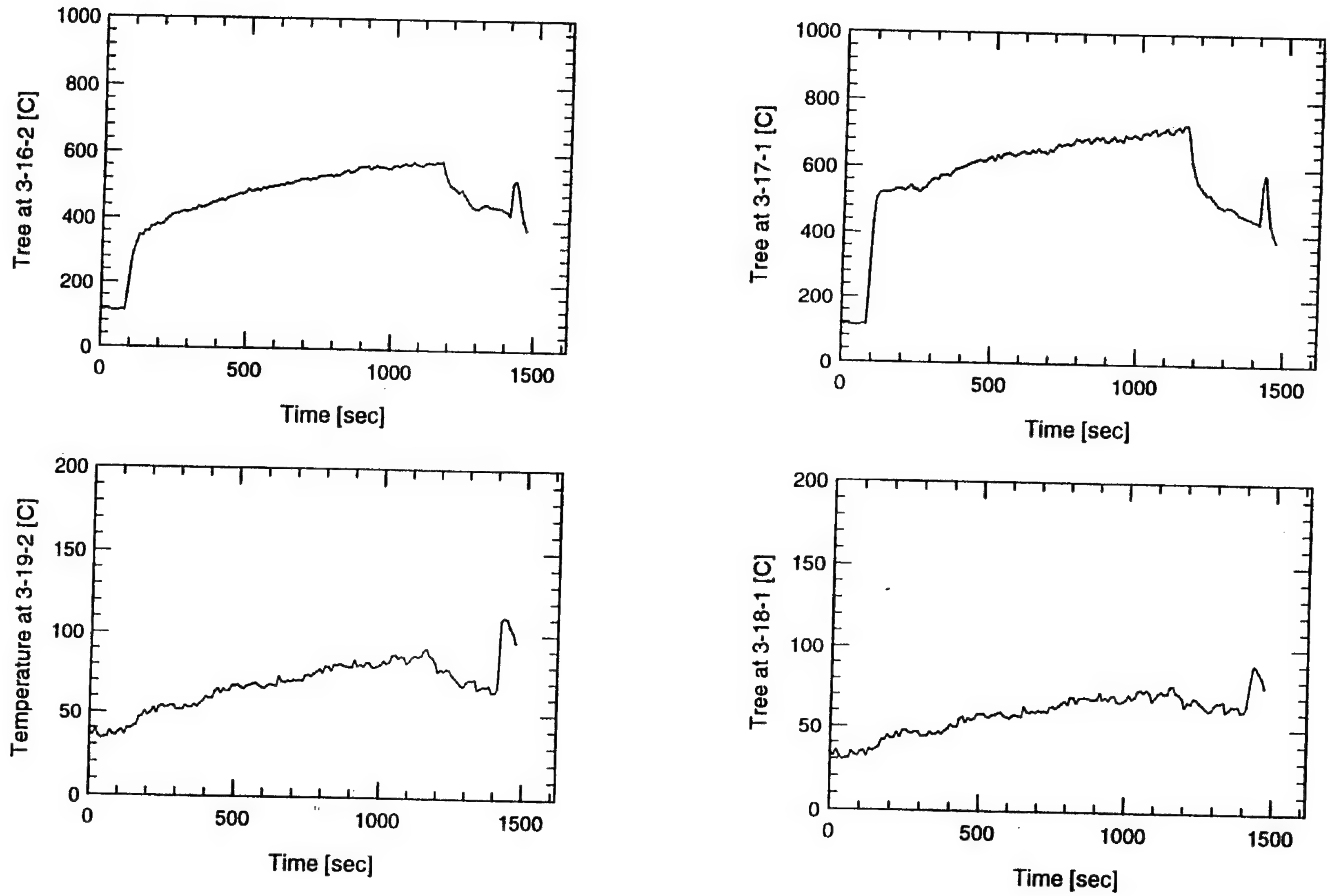

Fig. 22 - Typical, vertically averaged gas temperatures in the fire space (upper plots) and in the buffer zone (lower plots) for a backdraft test aboard the ex-USS SHADWELL (test SBD27).

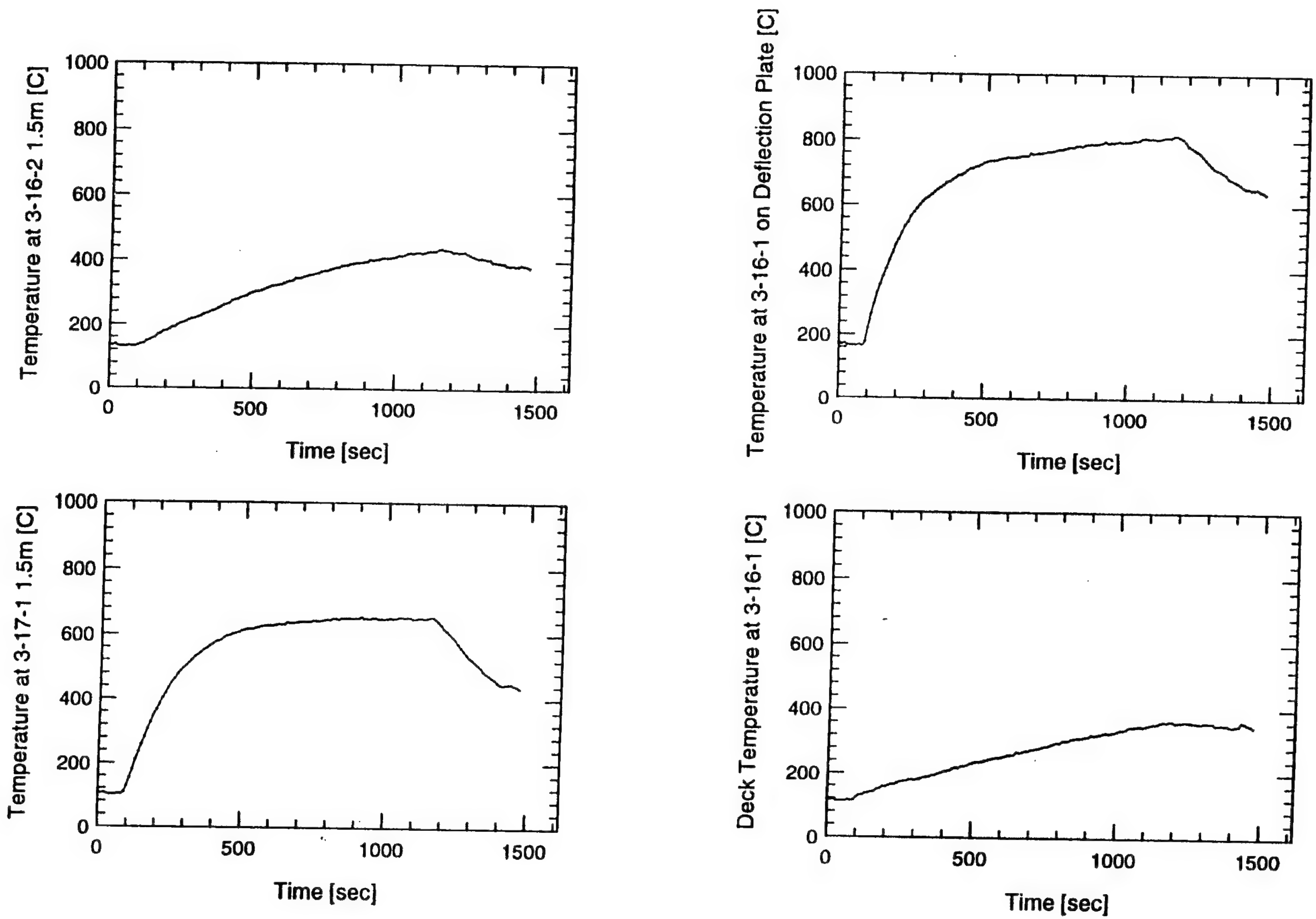

Fig. 23 - Typical surface temperatures within the fire space for a backdraft test aboard the ex-USS SHADWELL (test SBD27).

The fuel supply rate shown in Fig. 20 illustrates when the fire door was closed at 1161 seconds and the secondary fuel was injected between 1222 and 1289 seconds. After the door was closed, the species concentrations in the lower section of the fire space (Fig. 20) rapidly approached the same levels as high in the space, about 4 percent CO and 1 percent O_2. These data indicate that the space was fairly well mixed and uniform at the time the fire door was opened at 1402 seconds. The temperature data support the same conclusion. The top plots in Fig. 22 show the vertically averaged temperatures in the port (3-16-2) and starboard (3-17-1) sides of the fire space were both about 440°C at the time the door was opened. Average fire compartment temperatures were typically between 380°C and 420°C and oxygen concentrations high and low in the space was typically 0.5 to 1 percent.

Thirteen seconds after the door was opened (1415 seconds) a fire ball exploded out of the compartment filling approximately 60 percent of the buffer zone. Over the 13 second delay, there were no clear physical signs outside the fire space of the oncoming blast. In the majority of tests, the deflagration could be seen originating low in the starboard side of the fire compartment. The blast from the explosion is indicated on the temperature plots as a spike in temperature. As can be seen in Fig. 22, the average gas temperature rises rapidly both in the fire space (upper plots) and in the buffer zone (lower plots). The ignition of the fuel-air mixture in the fire space occurred via hot surfaces in the space. Fig. 23 shows plots of four surface temperatures within the space. The minimum bulkhead or deck temperature was 360°C at the time the door was opened (1402 s). This temperature is significantly higher than the 250°C autoignition temperature of diesel fuel. For most tests, the interior surfaces of the fire space (i.e., bulkheads, deck and overhead deflection plate) were at an average temperature ranging from 350°C to 450°C prior to the door being opened.

Depending on the buffer zone configuration and ventilation setup, the explosions produced varying sized fire balls which, particularly for the smaller buffer zone configurations, penetrated beyond the buffer zone boundaries. For example, during Buffer Zone 1 and 2 tests, blasts of flame extended as high as 3.4 m (11 ft) above WTH 2-20-2 for 4 to 15 seconds. However, flames never extended through the buffer zone door for Buffer Zone 1 or Buffer Zone EGR tests. In general, fire balls filled about one half to two-thirds of Buffer Zone EGR and filled the entire space of Buffer Zones 1 and 2.

The force of the gases rushing through the buffer zone doors was estimated by the Safety team to be enough to knock a man over. In some cases the blasts blew open QWTD 3-18-3 and WTS 1-19-2; both were shut but not secured. QWTD 3-18-3 was a door on the starboard side of Buffer Zone EGR (Fig. 5) and Buffer Zone 1 (Fig. 6). The scuttle, WTS 1-19-2, was located in the overhead of the second deck test area. During backdraft tests with closed boundaries, smoke curtains and clips became projectiles flying for distances of 8.5 m (28 ft) before hitting adjacent bulkheads.

As indicated by the results, the blast phenomenon is identified by a transient change in parameters, such as pressure, temperature and particle velocity. The shape of the blast wave is dependant on the explosion process and the physical surroundings. A relatively slow combustion process will produce a low-amplitude pressure wave where as a rapid combustion process will produce a sudden change in properties due to a shock wave. Time scales for the two types of events would be on the order of a few seconds and tens of milliseconds, respectively. For the backdraft explosions studied, the deflagrations were relatively slow, thus producing measured differential pressure waves that lasted for about two seconds. An example of a typical pressure time history for a Series 3 test is presented in Fig. 24. Fig. 24 shows the

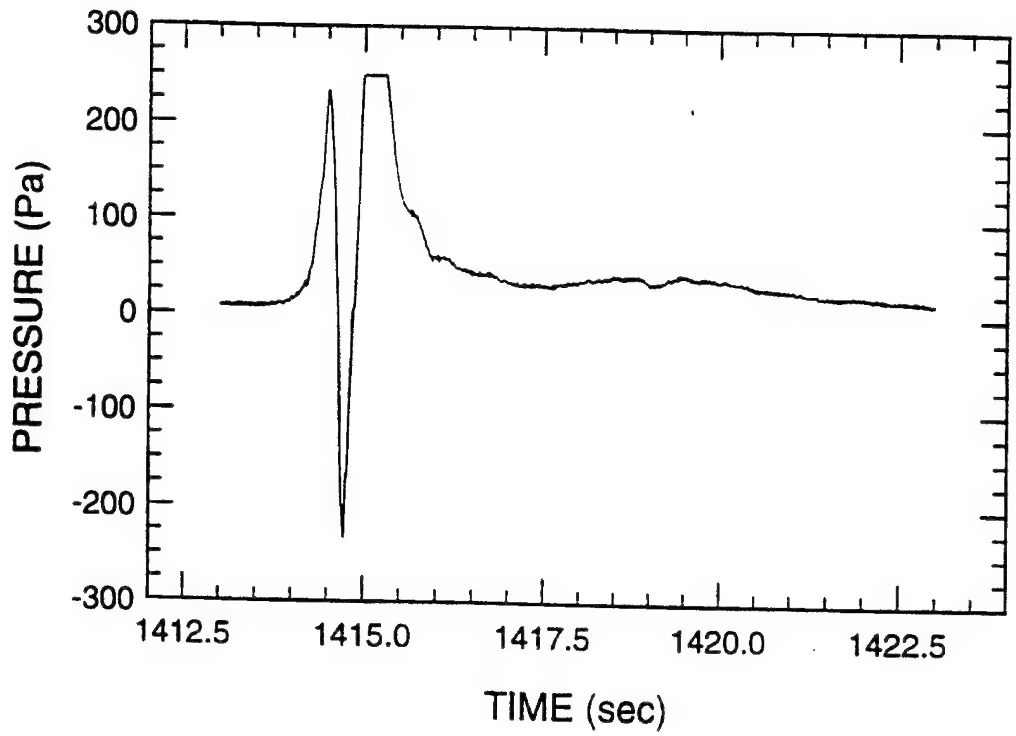

Fig. 24 - A typical time history of the differential blast pressure between the fire space and the Buffer Zone for a Series 3 backdraft test resulting in an explosion (test BD86).

differential pressure measurement between the fire space and the buffer zone for test SBD27 at the time the backdraft occurred. At a time of 1414 seconds, the pressure rapidly increases during the deflagration due to the expanding gases. The sharp drop in the differential pressure at about 1414.8 s is attributed to the formation of the fire ball, which momentarily creates a larger absolute pressure rise in the buffer zone than in the fire compartment. After the fire ball, the differential pressure quickly increases to greater than 250 Pa (the maximum output of the transducer) as residual fuel continues to burn out in the fire compartment. For Series 3 tests (SBD01 to SBD35) the peak pressure differential across the fire compartment bulkhead was typically less than 250 Pa, ranging from 85 to 234 Pa (the pressure transducer overranged at 250 Pa for tests SBD27 and SBD28). With the smaller buffer zones (1 and 2) the peak pressures were greater than 250 Pa, with a maximum of 1243 Pa. These results demonstrate that decreasing the size of the buffer zone space increases the explosion overpressure. The results were inconclusive for establishing trends for tests of the same buffer zone configuration with varying ventilation schemes and closures. Although several tests show a trend of an increasing blast pressure due to closing the buffer zone with smoke curtains, the data is not consistent for all tests. There was considerable variation in the data for tests of the same test scenario. For example, SBD23, SBD28, SBD32 and SBD33 were all Buffer Zone EGR tests with full ventilation; however the compartment peak pressures ranged from 85 Pa to over 250 Pa.

6.3.2 Effect of Buffer Zone and Ventilation Conditions

The results of this study show that active desmoking can safely improve tenability of the buffer zone for Class B fires. Tables 10-12 show for each buffer zone, respectively, the trend of increasing temperature within the space as ventilation is secured and the buffer zone is closed via smoke curtains and blankets. For example, with the EGR Buffer Zone configuration, Table 10 shows a 30°C increase from 67°C (153°F) to 96°C (205°F) as the space was changed from being fully ventilated with doors open to being buttoned-up (i.e., fans secured and boundaries closed with smoke curtains). The smaller buffer zone configurations were observed to have even higher temperature rises for the same change of ventilation conditions. The average gas temperature increased 48°C for Buffer Zone 1 and 72°C for Buffer Zone 2. Table 11 also indicates an increase in the percent obscuration due to smoke in Buffer Zone 1 as the boundaries and ventilation are secured.

Table 10. Comparison of Tenability Conditions within the EGR Buffer Zone for Different Ventilation Scenarios Prior to Opening Fire Door

Ventilation	Tests	Average Temperature (°C)*	
		3-19-2	3-19-1
Full	32,33	67 (3)	60 (4)
Smoke Curtains; Fans 100%	39	81	82
Smoke Curtains; Fans 25%	30	86	84
Smoke Curtains; Fans Secured	31, 35	96 (4)	97 (6)

* Values in parentheses are standard deviations

Table 11. Comparison of Tenability Conditions within Buffer Zone 1 for Different Ventilation Scenarios Prior to Opening Fire Door

Ventilation	Tests	Average Temperature (°C)*		Optical Density* (% Obscuration)
		3-19-2	3-19-1	
Full	39, 46, 57, 62	68 (6)	60 (4)	19 (18)
Boundaries Open; Box Fans	43, 61	83 (17)	84 (18)	12 (5)
Boundaries Open; Fans Secured	44	96	97	20
Smoke Curtains; Fans 100%	40, 60	125 (10)	130 (2)	21 (8)
Smoke Curtains; Fans Secured	41, 48, 59	106 (17)	114 (17)	48 (22)

* Values in parentheses are standard deviations.

Table 12. Comparison of Tenability Conditions within Buffer Zone 2 for Different Ventilation Scenarios Prior to Opening Fire Door

Ventilation	Tests	Average Temperature (°C)*	
		3-19-2	3-18-1
Full	50	65	N/A
Smoke Curtains; Fans Secured	53, 54, 56	141 (17)	N/A

* Values in parentheses are standard deviations.

The effect of decreasing the buffer zone size is also shown in Table 13. Table 13 shows the size and the average gas temperature of each of the three buffer zone configurations for the case of closed boundaries and no ventilation. As can be seen, the average temperature for the smallest space (Buffer Zone 2) is 141°C (286°F) which is about 55°C higher than the temperature in the largest space (Buffer Zone EGR).

Table 13. Average Gas Temperature in Buffer Zone at 3-19-2 for Tests with Closed Boundaries and No Ventilation (Smoke Curtains, Fans Secured) Presented for Different Buffer Zone Sizes

Buffer Zone	Size		Temperature (°C)*
	(m^3)	(ft^3)	
EGR	191	6729	96 (4)
1	104	3657	106 (17)
2	20	715	141 (17)

* Values in parentheses are standard deviations.

The test results also demonstrated that decreasing the size of the buffer zone increased the intensity of a Class B explosion originating from within the fire space. Fig. 25 illustrates the effect of decreasing the buffer zone size on the development of a Class B explosion in a buffer zone with open boundaries and full ventilation. The Figure shows the average of the peak temperature rises in the buffer zone due to the explosion and resulting fire ball. Decreasing the buffer zone size did not prevent backdraft explosions from occurring. On the contrary, this intensified the blast. Fig. 25 shows the peak temperature rise in Buffer Zone EGR was about 30°C (86°F). Tests with the smallest buffer zone, #2, were observed to have a peak temperature increases of 170°C (338°F). Fig. 26 shows similar results for tests in which the buffer zone was secured with smoke curtains and blankets and ventilation was secured. The Series 3 to 5 results also demonstrate that decreasing the size of the buffer zone space increases the explosion overpressure between the fire space and the buffer zone.

For a given size buffer zone, the results showed that securing the boundaries increased the intensity of a Class B explosion originating from within the fire space. Fig. 27 illustrates the effect of securing buffer zone boundaries on the development of Class B explosions in tests with Buffer Zone EGR. The Figure shows the average of the peak temperature rise in the buffer zone due to the explosion and resulting fire ball. As can be seen there was a distinct increase in the thermal blast to the buffer zone. Peak temperatures increased by about 32°C (90°F) for fully ventilated tests to 68°C (154°F) for tests with closed boundaries and no ventilation (i.e., Smoke Curtains-Fans off). The same trend in peak temperature rises due to Class B explosions is seen in Fig. 28 for the tests with Buffer Zone 1.

Fig. 28 also serves to demonstrate the difference between the effect of ventilation and boundary closures on backdraft explosion intensity. The bar graph shows that the explosion intensity is more dependant on buffer zone boundary conditions rather than ventilation. The first three bars in the graph show the average of the peak temperature rises observed for tests in which the buffer zone boundaries remained open and ventilation was varied. Forced ventilation varied from 4.5 m^3/s (9600 cfm) for Full Ventilation to 0.7 m^3/s (1500 cfm) for Box Fans (i.e., active desmoking) to no forced air flow. The two bars on the right show the average peak temperature rise observed for tests in which the buffer zone boundaries were closed using smoke curtains and blankets. In one case there was forced ventilation through the second deck space, and in the other ventilation was secured. The tests with boundaries secured had similar temperature rises of 140 to 150°C which is about 70°C higher than the open boundary tests. The exception is the test in which the buffer zone boundaries were open and box fans were used for active desmoking. Other than this test, the open boundary tests had similar temperature rises of 75 and 60°C. The higher temperature observed for the Box Fan scenario is actually associated with tighter boundaries. Although the buffer zone boundaries were the same for all the open boundary cases, the Box Fan scenario required secondary boundaries outside of the buffer zone to be secured. As a result, the explosion had fewer pathways (and total flow area) to vent to weather in the Box Fan scenario as compared to the two other open boundary scenarios. Even with this variation, it can be seen from the Figure that closing the buffer zone boundaries had a larger effect on the explosion intensity compared to changes in ventilation flow rates.

7.0 DISCUSSION

The following section discusses three main topics. The first is the correlation between the fuel mass fraction and the creation of a Class B explosion. The second is the effect of buffer zone and ventilation conditions on the development of a Class B explosion. The last topic is the use of water spray as a firefighting tactic for explosion mitigation.

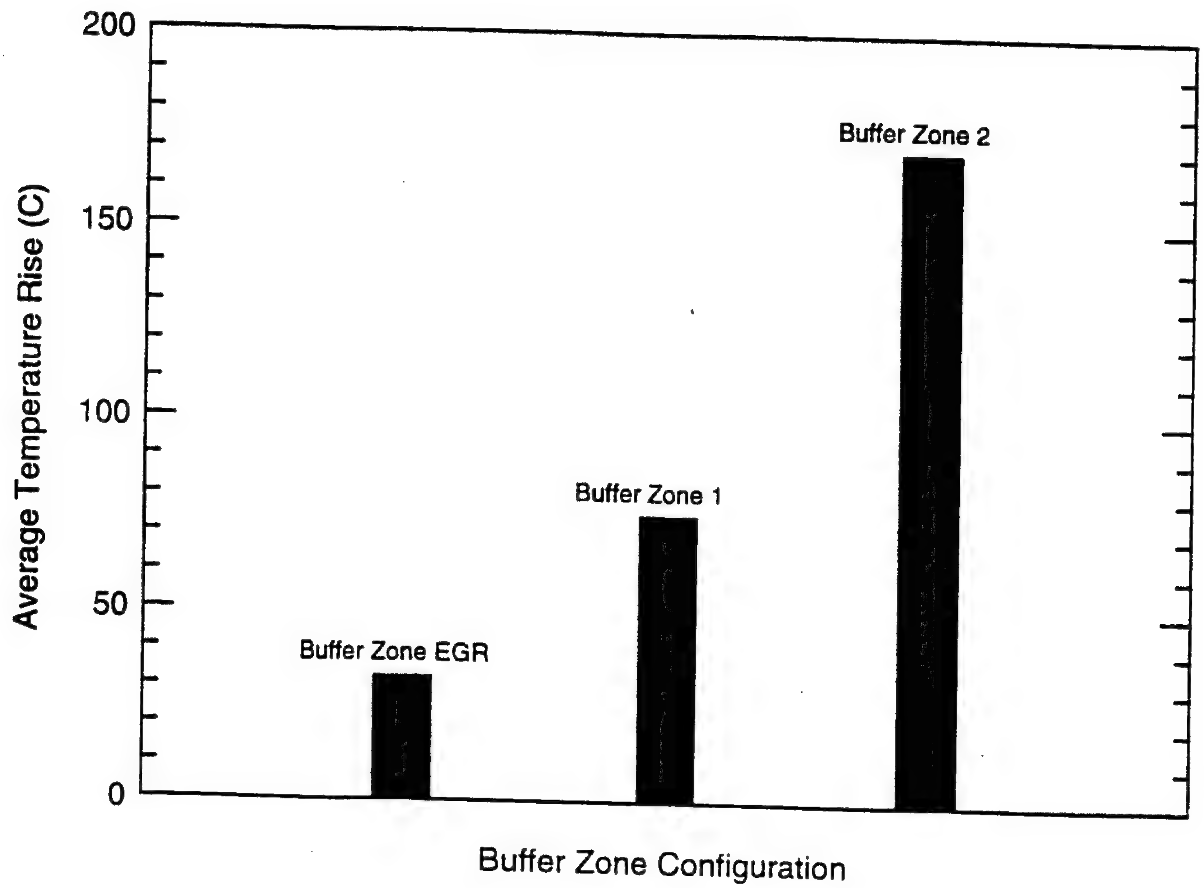

Fig. 25 - Average temperature rise due to Class B explosions in buffer zones with full ventilation and boundaries open.

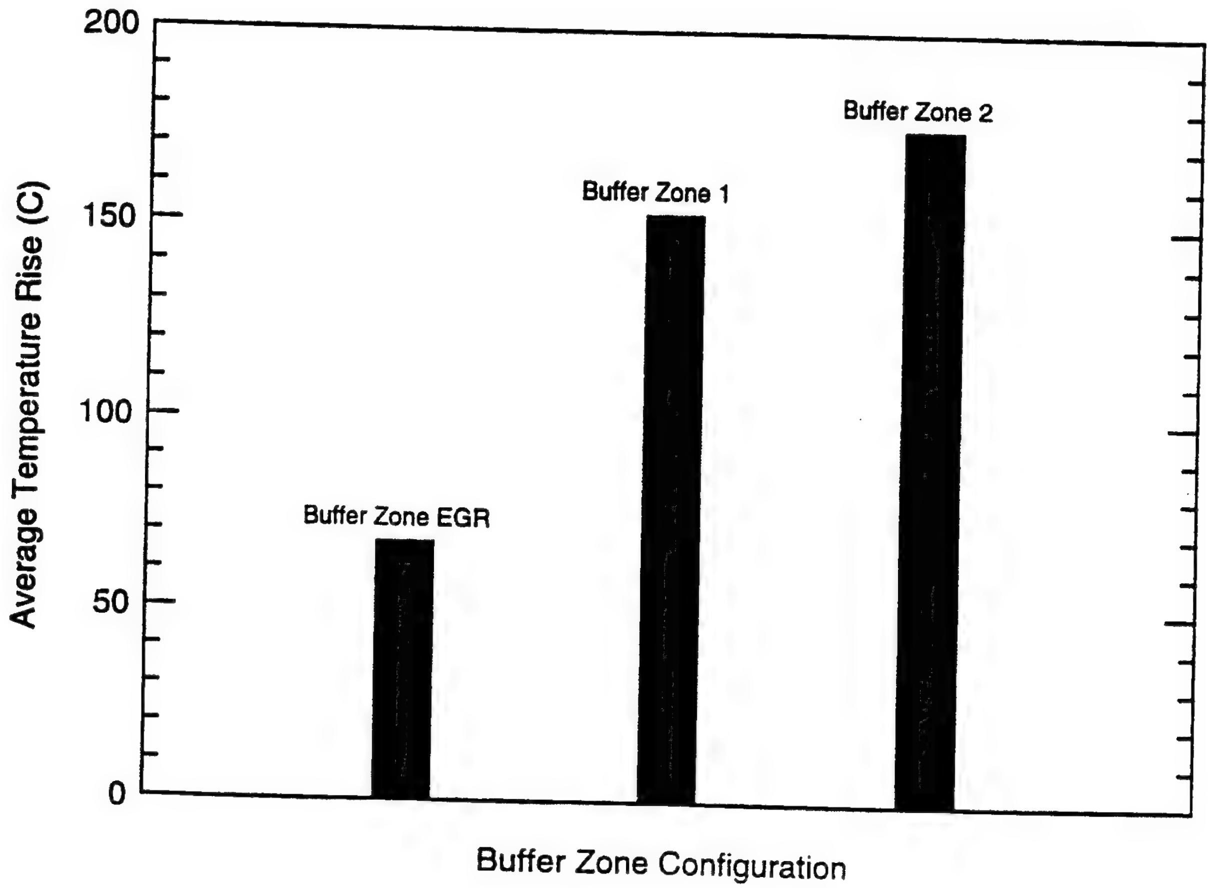

Fig. 26 - Average temperature rise due to Class B explosions in buffer zones with no ventilation and boundaries secured.

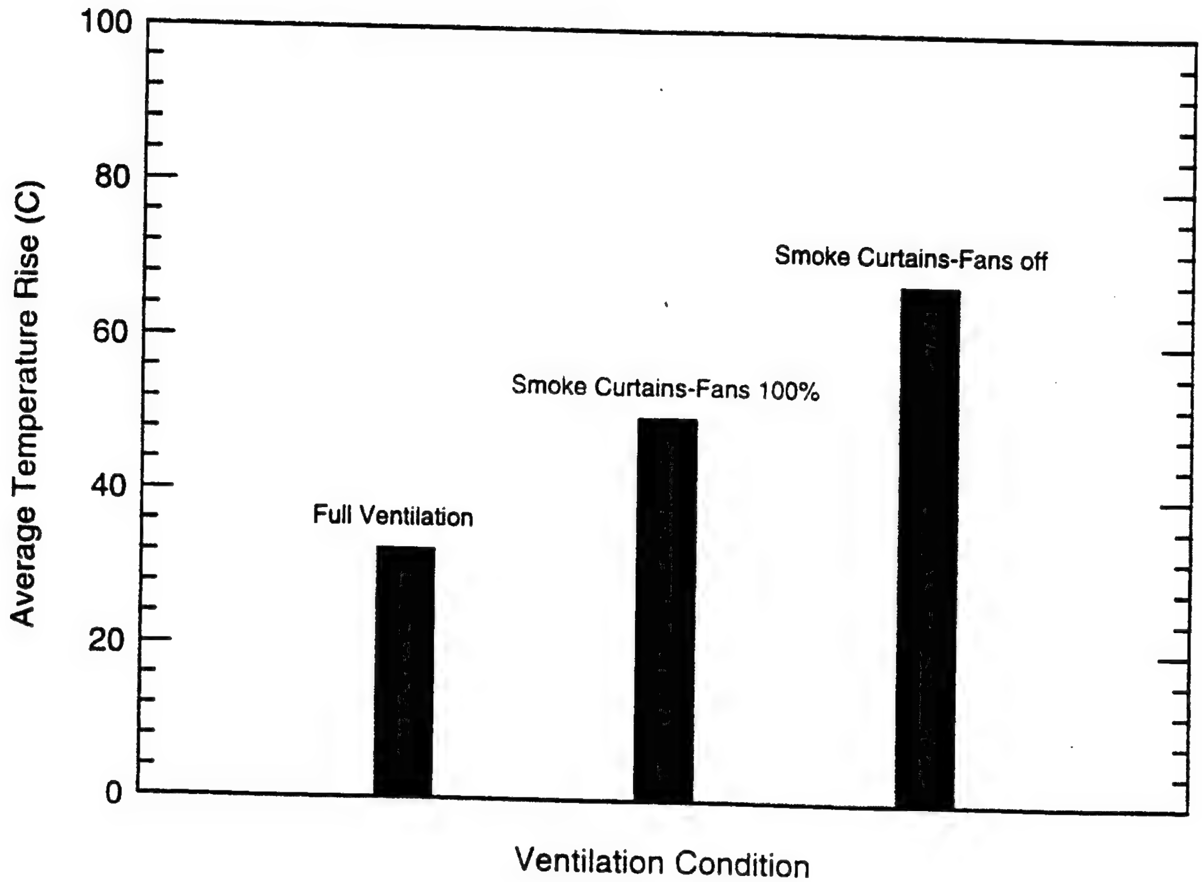

Fig. 27 - Average temperature rise due to Class B explosions in Buffer Zone EGR with different ventilation schemes.

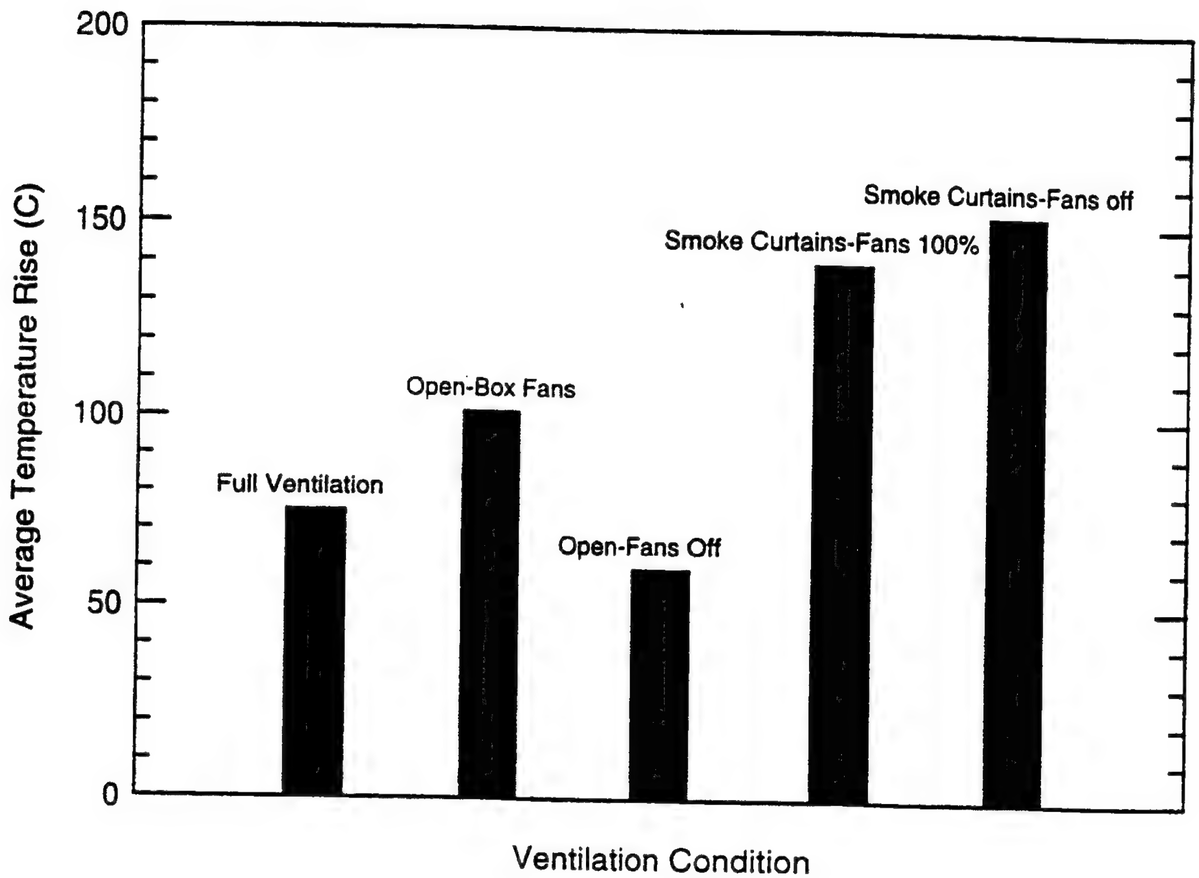

Fig. 28 - Average temperature rise due to Class B explosions in Buffer Zone 1 with different ventilation schemes.

7.1 Fuel Mass Fraction

The results of all test series (both CBD and ex-SHADWELL tests) show that there is a very well defined correlation between the nominal fuel mass fraction and the occurrence of a No. 2 diesel explosion. Simply, fuel mass fractions of 0.16 or higher are needed for the creation of Class B explosions in highly vitiated environments. Fig. 29 shows the frequency with which backdraft explosions occurred as a function of the nominal fuel mass fraction, Y_f, in the fire space. These data include results from 76 tests from Series 2B (tests BD73-BD115) through Series 5. Series 2 tests BD1-BD73 have not been included since the problems of wind and soot build up introduce secondary variables that artificially skew the results. Next to each data point is the number of valid tests conducted at the specified fuel mass fraction. As can be seen in Fig. 29, no backdraft explosions occurred for tests with fuel mass fractions of 0.15 or less. Fuel mass fractions between 0.15 and 0.18 represent a transition region from fuel loading conditions unable to create an explosion to fuel loadings that do. Except for 1 test out of 51 (i.e., at Y_f of 0.20), all tests with fuel mass fractions of 0.18 or higher resulted in an explosion with a fire ball. For discussion purposes, a value of 0.16 will be considered as the critical fuel mass fraction needed to create a Class B explosion.

A brief discussion of flammability is presented as background to the concept of a critical fuel mass fraction. A more detailed discussion is presented in reference (1). The lowest concentration of a gaseous fuel in air which can be ignited and propagate a flame is known as the lower flammability limit (LFL). Likewise, the highest concentrations which will burn is defined as the upper flammability limit (UFL). An explosion is only possible for fuel-air mixtures between the LFL and UFL. Flammability limits and explosive limits can be used interchangeably here. Flammability limits for gaseous fuels are routinely defined in terms of the volume percent of fuel in air. An alternate representation can be given in terms of mass of fuel per volume of mixture. Fig. 30 from Drysdale (reference (6)) and data from Zabetakis (reference (7)) shows the correlation of flammability limits with respect to molecular weight (expressed as carbon number) for n-alkanes. The data are presented in both volume percent and mass fraction. The Figure shows that the lower flammable mass concentration for hydrocarbon fuels in air is approximately constant at 45 to 50 g/m^3. In terms of volume percent, this corresponds to about 0.5 to 1 percent in air. The lower flammability limit for the number 2 diesel fuel used in this study is about 0.7 percent based on a molecular formula of $C_{10}H_{19}$. Number 2 diesel is very similar in combustion properties to fuels such as F76 and kerosene. Unfortunately, there is little published data on flammability limits for all of these fuels. However, it can be accepted that a LFL of 0.6 to 1.2 is typical as illustrated by the data in Fig. 30.

The fuel mass fractions corresponding to the lower and upper flammability limits for diesel fuel are approximately 0.03 and 0.19, respectively. The critical fuel mass fraction of 0.16 observed in this study is considerably higher than the LFL of 0.03. The reason that the critical fuel mass fraction does not equal the LFL is two-fold. The LFL is based on a mixture of fuel in air, whereas for the current study the critical fuel mass fraction consists of fuel in combustion products with minimal oxygen. The second reason is that the LFL corresponds to a pre-mixed system. The backdraft phenomenon consists of mixing of two flow streams to form a diffusion flame. The mixing process requires a critical fuel mass fraction greater than the LFL, such that as the gases mix the fuel-air mixture will be equal to or greater than the LFL. If a mixture consisted of fuel in highly vitiated combustion products (O_2<10%) at a fuel concentration equal to the LFL, it would not be able to ignite because as soon as air is mixed with the fuel the original gas mixture would become diluted and the fuel concentration would decrease below the LFL.

The concept of a critical fuel mass fraction can be illustrated using a standard flammability diagram as shown in Fig. 31. To the authors' knowledge, a specific diagram for diesel fuel or similar does not exist, except for the general data presented in Fig. 30.(It should be noted that

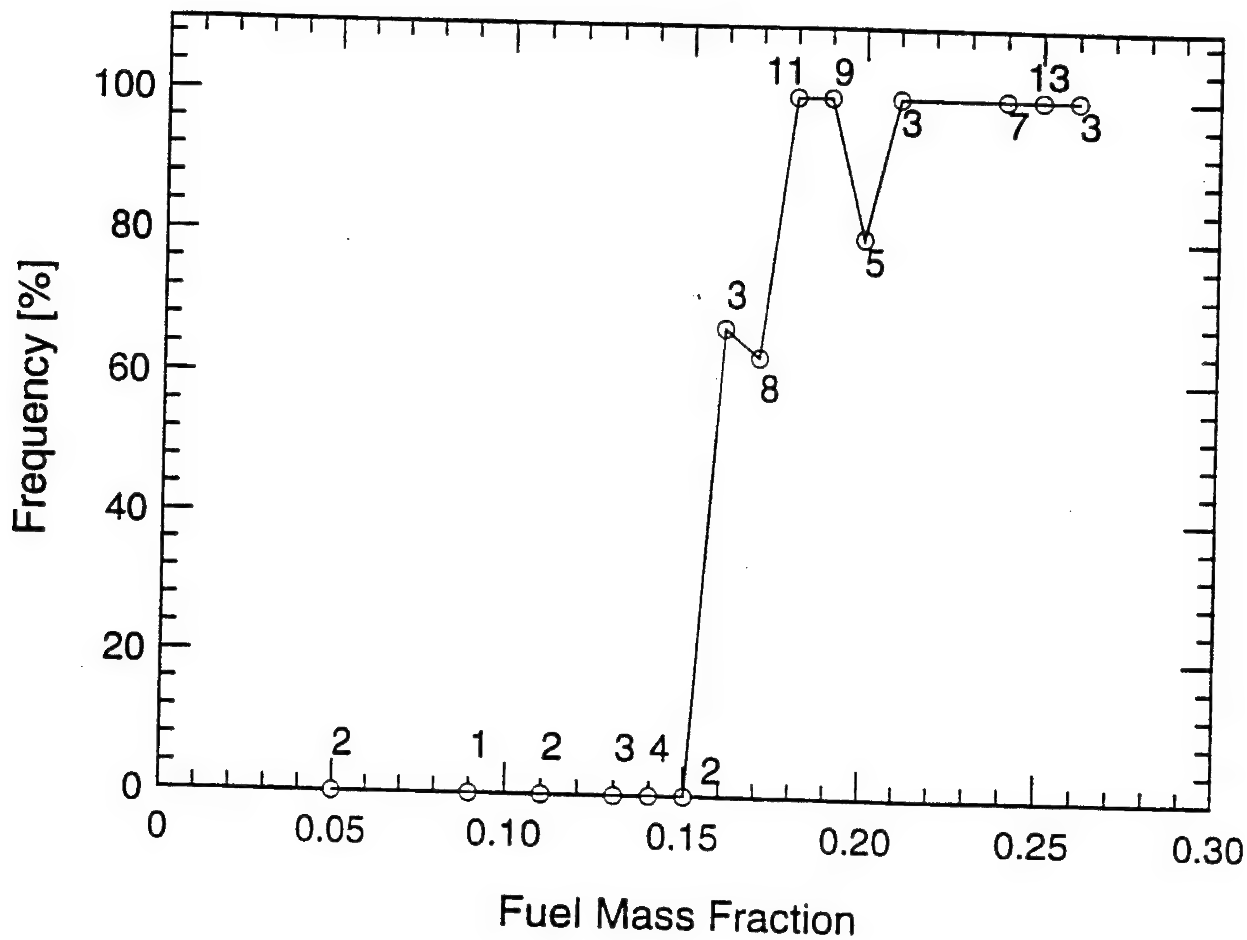

Fig. 29 - The frequency of occurrence of backdraft explosions with respect to the monomial fuel mass fraction.

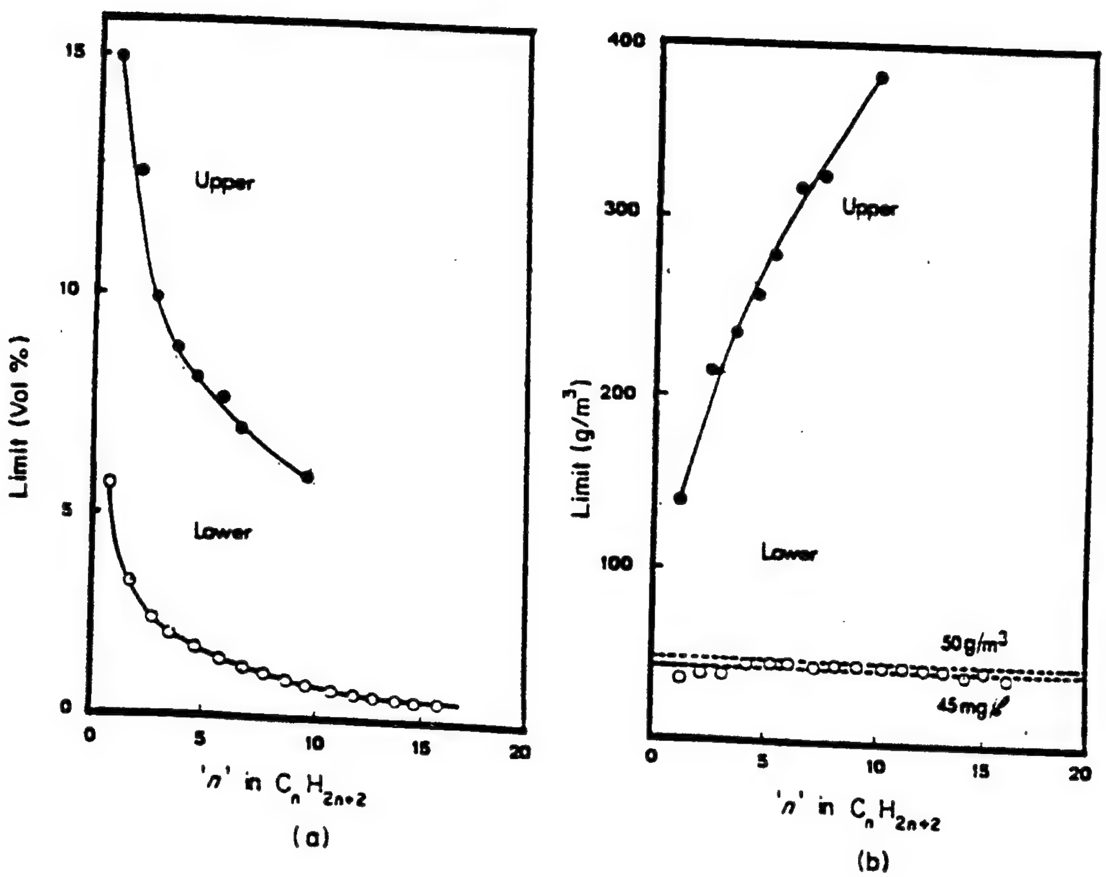

Fig. 30 - Lower and upper flammability limits in air of various hydrocarbons expressed as a volume percent and on a mass basis (figure taken from Drysdale [6], data is from Zabetakis [7]).

this methane diagram is for illustrative purposes and should not be used to calculate actual composition for other hydrocarbon fuels.) Therefore, Fig. 31 uses a diagram for methane fuel mixed with oxygen and nitrogen. The flammability diagram consists of three axes representing the concentration of fuel (methane), oxygen, and nitrogen. Each axis shows the concentration of each of the three constituents from 0 to 100% by volume. Although presented in percent volume (per standard practice) the axes can be interpreted as mass fraction since the values are directly proportionate to the ratio of constituent molecular weights.

As can be seen in the Fig. 31, all mixtures within the designated envelope are flammable (explosive). For mixtures with fuel and oxygen only (the left axis is a line of 0% nitrogen), the diagram indicates that the LFL and UFL correspond to 5 percent and 60 percent fuel, respectively. The envelope originating at these points designates the flammable mixtures of fuel in oxygen and nitrogen. The line from point A to the apex of the diagram is a line of constant proportionality between oxygen and nitrogen corresponding to air. It follows that any mixture of methane and air will fall along this line. The points at which the line intersects the flammability envelope correspond to the LFL and UFL of methane in air.

Consider a fire compartment that has been depleted of oxygen, and thus, the fire has extinguished. The fuel source may or may not have been secured. The flammability diagram will be used to illustrate the two primary conditions that can be created in the fire space depending on the amount of unburned fuel that is volatilized in the space. The combustion products are represented by nitrogen. Point B designates a mixture of 10 percent fuel and 90 percent nitrogen. Line B-A shows the varying mixture compositions that will be created if a door to the space was opened allowing fresh air to flow into the compartment and mix with the composition designated by point B. Since this line does not intersect the flammability envelope, a flammable mixture will never be created, and thus, an explosion cannot occur.

Point C represents an initial mixture of 18 percent fuel and 82 percent nitrogen (i.e., combustion products). Line C-A shows the varying mixture compositions that will be created if a door to the space was opened allowing fresh air to flow into the compartment and mix with the composition designated by point C. Since line C-A is tangent to the flammability envelope, it represents the minimum fuel mass fraction necessary to obtain a flammable mixture once mixed with air. Therefore, for an initial mixture of fuel and nitrogen only, the critical fuel mass fraction corresponds to that at point C. As can be seen from the diagram, any mixture with a fuel concentration greater than 18 percent (e.g., point D) will result in a flammable mixture after it is mixed with sufficient air. This is illustrated by the intersection of line D-A with the flammability envelope.

The above illustration (Fig. 31) demonstrates the concept of a critical fuel mass fraction for an initial mixture containing fuel and combustion products with no oxygen. This scenario is closely representative of the backdraft work performed in this study. However, it is reasonable to expect that conditions may arise in which oxygen concentrations are not zero. Comparison of Fig. 32 to Fig. 31 illustrates the relationship between the critical mass fraction and the initial oxygen concentration. Fig. 32 is similar to Fig. 31 except it shows initial mixtures with oxygen concentrations of 10 percent. The dashed line between the point at 10 percent oxygen (bottom axis) and 90 percent methane (left axis) represents all mixtures consisting of 10 percent oxygen.

Similar to the discussion above for Fig. 31, point C is the mixture corresponding to the critical fuel mass fraction for mixtures with 10 percent oxygen. In this example, 10 percent methane is the minimum fuel concentration necessary to develop an explosive mixture once it is mixed with

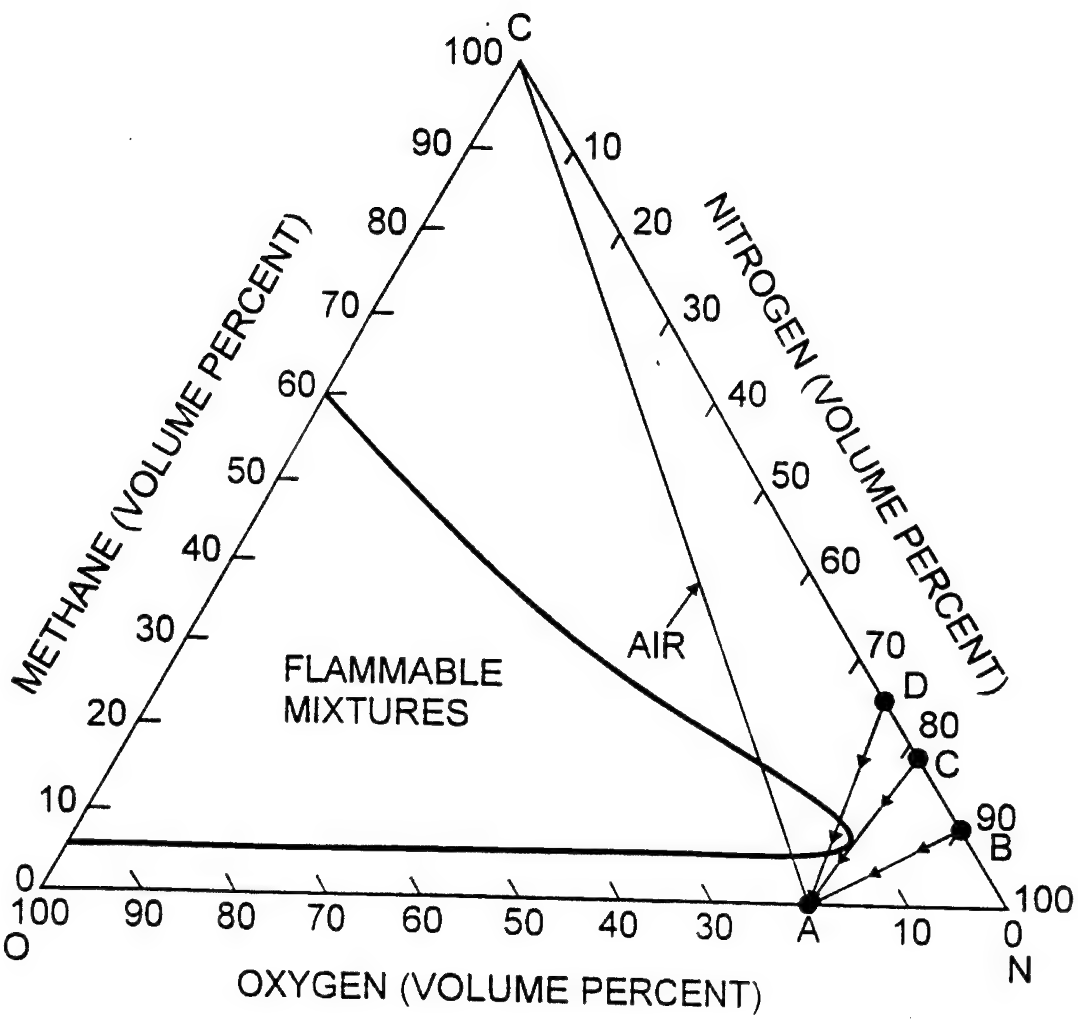

Fig. 31 – A typical flammability diagram showing the possible mixture compositions that can result from mixing air with one of three initial mixtures (B, C and D) of methane and nitrogen with zero percent oxygen (for illustration only).

air. Initial mixtures with fuel concentrations less than 10 percent (e.g., Point B) will never produce an explosive mixture. This is illustrated by the fact that the line B-A does not intersect the flammability envelope. Initial mixtures with fuel concentrations greater than 10 percent can produce flammable mixtures since the addition of air is represented by the line D-A which intersects the flammability envelope.

Figs. 32 and 31 illustrate how the critical fuel mass fraction will decrease as the oxygen concentration in the initial mixture increases. In these examples, the critical fuel concentration was 18 percent for the case of zero percent oxygen and 10 percent for the case of ten percent oxygen. The case of zero percent oxygen is a bounding case as it represents the maximum possible value of the critical fuel fraction. Therefore, according to the results of these tests a critical fuel mass fraction of 0.18 is nearly the maximum possible value since the oxygen concentrations were near zero (0.5 to 1% vol.).

Within the published literature, there is only one other known study of backdraft explosions. This work was performed by Fleischmann for excess methane in a reduced scale enclosure (reference (8)). The 3.6 m^3 (128 ft^3) enclosure measured 1.2 m by 2.4 m by 1.2 m high (4 by 8 by 4 ft) and corresponds to about 10 percent of the size (volume) of the spaces studied in this work. A methane burner was ignited within the closed enclosure. The fire would extinguish as the oxygen concentration decreased and the fire became oxygen starved. The fuel was allowed to flow for a set period after extinguishment at which time a hatch was opened at one end of the enclosure. An electric spark positioned near the burner was used as an ignition source. The gravity current of air and the deflagration within the compartment were visible through a glass window in one side of the enclosure. Two vent configurations were studied: (1) a horizontal opening 0.4 m high by 1.1 m wide and (2) a window-style opening 0.4 m by 0.4 m, both centered on the short wall of the compartment at the opposite end from the burner.

Fleischmann conducted tests with fuel mass fractions up to 0.29 and states that the results "show that the HC [hydrocarbon] concentration must be >10% [by mass] in order for a backdraft to occur. When the HC concentration is <10% the flame travel is slow and the compartment overpressure is much lower. As the HC concentration increases the compartment overpressure increases and the backdraft becomes more severe." The results of Fleischmann indicate a lower critical fuel mass fraction than that observed in this study for backdrafts in full-scale enclosures with a typical ventilation opening (i.e., a door instead of a raised horizontal slot). The difference is attributed to the oxygen concentrations within the compartments. Average compartment oxygen concentrations for this study were approximately 1 percent, where as the average oxygen concentrations in Fleischmanns tests were estimated to be about 10 percent or higher.[1] As illustrated above with Figs. 31 and 32 gas mixtures with higher oxygen concentrations require lower levels of fuel to create an explosive condition.

Table 14 shows selected data from Fleischmann's experiments (reference (8)) for tests of both vent opening configurations. Presented in the Table is the fuel flow rate, the mass fraction of total hydrocarbons in the upper layer (UL), the mass fraction of oxygen, the ignition delay time, the peak pressure, and the estimated fire ball size. In comparing the data for the horizontal slot and the smaller window opening, it can be seen that backdrafts were more difficult to create with the window opening. Despite relatively high fuel mass fractions of 0.15 to

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[1]The results of Fleischmann are estimated since he presented all species data as mass fractions; typical oxygen levels in the upper layer were 0.11 with slightly higher levels in the lower layer (about 0.15). The volumetric concentration has been calculated based on a mass fraction of 0.11 and an assumed molecular weight of the gas composition of 26 g/mole.

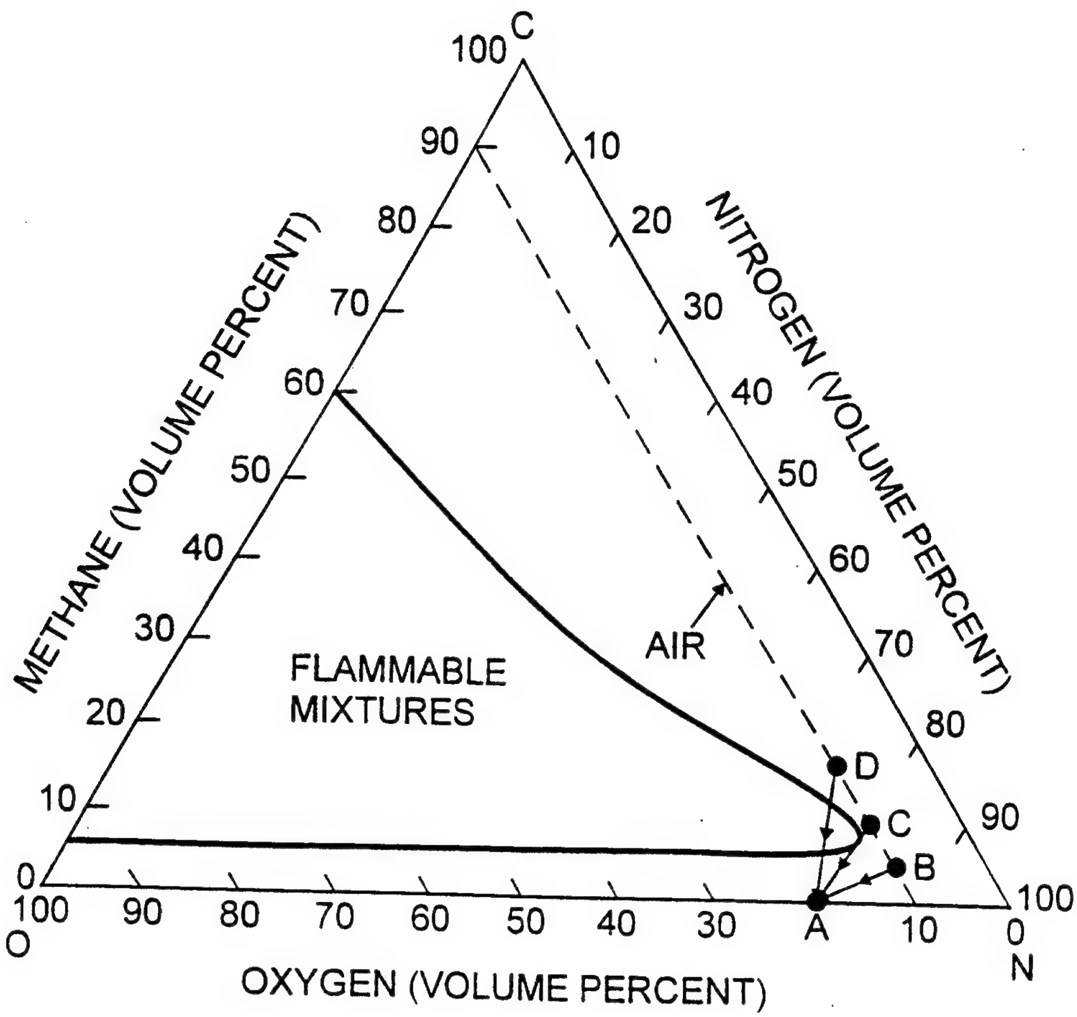

Fig. 32 – A typical flammability diagram showing the possible mixture compositions that can result from mixing air with one of three initial mixtures (B, C and D) of methane and nitrogen with ten percent oxygen (for illustration only).

0.18, five window opening tests did not result in a backdraft with a fire ball. The small peak pressures for these tests indicate that there was a deflagration although minor in intensity. The gas temperatures and oxygen mass fractions for the window opening tests were essential the same as those of the horizontal slot tests. Therefore, there was no apparent differences between test scenarios except for the vent configuration. These results indicate that the manner in which a space is ventilated impacts the probability of creating an explosive condition. It is uncertain whether the mitigating effect from the window style vent is due to a reduction in size or due to the different geometry. The smaller size vent decreases the mass flow rate into the enclosure. This is reflected in the longer ignition delay times. The reduced flow may limit the size of the mixing region which reaches a flammable level at the point of ignition, thus causing a weak deflagration that is unable to form an explosive fire ball. It is unclear how the change in geometry compared to the change in size effects the large scale vortices (i.e., the entrainment process) compared to the small scale vortices that impact the localized mixing of the fluid streams. Further work in this area is warranted to determine the most appropriate means to vent and reenter a Class B fire space. Several of the issues that need to be understood include: (1) does it matter if the space is vented from above rather than below or from the side (i.e., through a door) and (2) does the size of the reentry pont (a hatch, a door, a scuttle) significantly effect the mixing of gases, and thus the formation of an explosion.

Table 14. Selected results from Fleischmann [4] for methane backdraft experiments in a reduced-scale enclosure

Horizontal Slot Opening					
Fuel Flow (kW)	Y_{HC}	Y_{O_2}	Ignition Delay (s)	P_{max} (Pa)	Fire Ball (m)
200	0.10	0.04	6.27	8	1
72	0.10	0.09	5.27	4	0
72	0.12	0.11	5.36	6	2
200	0.13	0.04	4.27	14	0
72	0.14	0.11	6.43	9	2
72	0.16	0.11	6.63	28	3
69	0.16	0.11	5.47	43	3
69	0.19	0.11	(3.7)	73	4
69	0.19	0.12	5.40	43	4
77	0.20	0.11	5.67	40	4
71	0.20	0.11	5.63	33	4
73	0.21	0.12	(3.63)	50	4
68	0.22	0.12	5.70	49	4
70	0.22	0.12	6.60	39	4
200	0.24	0.05	6.73	22	2
200	0.29	0.06	(4.33)	8	0
200	0.29	0.06	5.27	36	4

Table 14. Selected results from Fleischman [4] for methane backdraft experiments in a reduced-scale enclosure (continued)

Window Opening					
Fuel Flow (kW)	(LL) Y UL HC	(LL) UL Y_{O_2}	Ignition Delay (s)	P_{max} (Pa)	Fire Ball (m)
70	(0.02)	(0.17)	25.50	14	0
70	(0.03)	(0.16)	25.00	115	4
70	(0.04)	(0.15)	30.40	102	4
70	0.15	0.11	10.33	2	0
72	0.17	0.11	15.00	13	0
72	0.18	0.11	20.47	9	0
72	0.18	0.11	15.03	22	0
72	0.18	0.11	15.00	189	4
75	0.19	0.11	20.13	82	4
74	0.20	0.11	20.00	258	5
73	0.20	0.11	25.27	213	5

(LL) indicates lower layer measurement, all others are upper layer

7.2 Buffer Zone and Ventilation Conditions

The results of this study show that active desmoking can safely improve tenability of the buffer zone for Class B fires. As was shown in Tables 10-12, the temperature within the buffer zone increased as ventilation was secured and the buffer zone was closed via smoke curtains and blankets. For example, with the EGR Buffer Zone configuration, there was a 30°C increase from 67°C (153°F) to 96°C (205°F) as the space was changed from being fully ventilated with doors open to being buttoned-up (i.e., fans secured and boundaries closed with smoke curtains). The smaller buffer zone configurations were observed to have even higher temperature rises for the same change of ventilation conditions.

These results are not unexpected as Class A FDE testing has shown that active desmoking can be used effectively to improve conditions for firefighters (references (9-11)). However, there remained concerns that active desmoking during a Class B fire could result in the transport of flammable gases and, thus, remote ignition away from the fire space. During the test series propane pilot flames were used in the flow path down stream of the fire space as remote ignition sources. At no time was ignition of the fire effluent observed. These test series, although in no way exhaustive, demonstrate that buffer zones in Class B Fires can be desmoked safely. In general, it is deemed safer to ventilate a space as soon as possible to prevent the build up of fuel vapors rather than secure the space which can potentially create a fuel-rich environment.

Decreasing the buffer zone size did not prevent backdraft explosions from occurring. On the contrary, the test results demonstrated that decreasing the size of the buffer zone increased the intensity of a Class B explosion originating from within the fire space. As was shown in Fig. 25, the peak temperature rise in Buffer Zone EGR was about 30°C (86°F). Tests with the smallest buffer zone, #2, were observed to have substantially higher peak temperature increases of 170°C (338°F). The Series 3 to 5 results also demonstrate that decreasing the size of the buffer zone space increases the explosion overpressure between the fire space and the buffer zone.

For a given size buffer zone, the results show that securing the boundaries (i.e., creating a dead-air space) also increased the intensity of a Class B explosion originating from within the fire space. This was illustrated in Fig. 31 which showed the effect of securing buffer zone boundaries on the development of Class B explosions in tests with Buffer Zone EGR. The averaged, peak temperatures increased by about 32°C (90°F) for fully ventilated tests to 68°C (154°F) for tests with closed boundaries and no ventilation (i.e., dead-air space). The results of Buffer Zone 1 tests also show the same distinct increase in the thermal blast to the buffer zone when it is made a dead-air space rather than keeping boundaries open. This study suggests that the underlying premise in NSTM 555 for creating a "dead-air space" in the buffer zone is not valid. Recall that Section 6.3.7.2 of NSTM 555 (reference (3)) states that establishing the dead-air space "buffer zone is important due to the possibility of fire or explosion if hot combustion gases from a Class B fire mix with fresh air." It is clear from this work that creating a dead-air space does not necessarily prevent or even mitigate an explosion or reflash from occurring. The mixing of air in the buffer zone and fuel gases in the fire space is driven by the thermally induced pressure gradient between the hot fire space and the cooler buffer zone. The creation of a dead-air space did not significantly impact this mixing process which occurred and resulted in a backdraft within only 30 seconds of opening the fire boundary. Such a short delay time precludes any feasible tactics, such as using a smoke curtain at the fire boundary reentry point, to prevent sufficient air from mixing with fuel to form a flammable mixture.

It may be rationalized that a sufficiently small buffer zone would not contain enough air, even if mixed entirely into the fire space, to form an explosive mixture. However, there are practical problems with this idea as explained further in this paragraph. Experimental limitations prevented the study of extremely small buffer zones relative to the fire space. The ratio of the volume of the buffer zone to the volume of the fire space ranged from 0.57 to 5.5 for the experiments conducted. A study of machinery spaces on LPD17 and DDG-51 ships shows that vestibules or trunks would be used as the immediate buffer zone for attacking a fire in the machinery space. If the buffer zone were limited to just these spaces, the volume ratio of the buffer zone to the fire space could be as small as 0.06 to 0.006. Due to the relatively small size of the buffer zone, as the fire space is entered, the buffer zone and fire space atmosphere would become essentially the same. Therefore, opening the fire space to the buffer zone would just marginally extend the fire zone boundaries. As a result, the potential for explosion would not be averted; the boundary that separates the fuel-rich atmosphere and fresh air has just been moved further from the fuel source. It is unclear whether there is an optimal buffer zone size at which the limited air in the buffer zone could prevent a potential explosion from occurring during reentry. It can be argued that any amount of air introduced into a Class B fire space could locally mix near the door or hatch to form an explosive mixture. This may be especially true for trunks opening into machinery spaces, since this is typically the location of fuel storage and, thus, a likely area to have high fuel concentrations from a break in the fuel system.

7.3 Water Spray

Both test series with the fire compartment venting directly to atmosphere (CBD tests) and the series venting to confined spaces (ex-USS SHADWELL tests) were successful in demonstrating

that water injection can be used as a mitigating tactic to suppress a Class B explosion or hazardous reflash. The effect of varying amounts of water injection on mitigating the backdraft phenomenon was clearly established in the Series 2 work at CBD. Table 15 shows the comparison of Series 2 water spray injection tests with the same initial conditions. That is each test consisted of 4.92 kg of secondary fuel injection corresponding to a pre-water injection fuel mass fraction of about 0.25. Table 15 shows that the strength and size of the backdraft explosions/fire balls decreased with increasing amounts of water injection. As the amount of water was decreased from 13.7 kg to 5.5 kg the severity of the backdraft phenomenon changed from full prevention of an ignition to creation of an explosion with a fire ball. At the highest injection level of 13.7 kg (3.6 gal) of water, no ignition or fire occurred at all.

Table 15. Comparison of Series 2B Backdraft Tests with Water Spray Injection for Tests with 4.92 kg of Secondary Fuel Injection

Test	Mass of Water (kg)	Volume of Water (gal)	Outcome of Backdraft Test
BD100	5.5	1.45	Fire ball (larger than BD98 and BD99)
BD99	8.2	2.17	Small fire ball
BD98	8.2	2.17	Small fire ball
BD90	10.9	2.9	Small fire ball (4 m extension from compartment)
BD114	10.9	2.9	Very weak pressure pulse, roll out of flame
BD96	10.9	2.9	No flame, no fire ball
BD102	13.7	3.63	No flame, no fire ball
BD95	13.7	3.63	No flame, no fire ball
BD93	13.7	3.63	No flame, no fire ball

The trend of mitigating and eliminating explosions with increasing water injection into the fire space correlates very well with the resulting fuel mass fraction in the fire space. Injection of water into the fire space results in a decrease in the fuel mass fraction due to dilution. In general, there was very good agreement with the criterion that fuel mass fractions greater than 0.15 are needed to produce a backdraft explosion. This result can be seen in Table 16 which shows the outcome of all backdraft tests with water spray injection. The tests are presented in ascending order of the nominal fuel mass fraction, Y_f, after water was injected. The second column in Table 16 shows the fuel mass fraction in the fire space before water was injected. In all cases, the fuel mass fraction before water injection was significantly above the critical fuel mass fraction needed to create a backdraft. Similar to the results for tests without water injection (Fig. 29), there are three principle regimes denoted by fuel mass fractions less than 0.16, equal to 0.16 or 0.17, and greater than 0.17. For most tests with fuel mass fractions after water injection of less than 0.16, no explosions or even flames out of the door occurred. Whereas, tests with fuel mass fractions of 0.16 or 0.17 represent a transitional range with outcomes of only flames out of the door to small fire balls. The third regime shows that backdraft scenarios with fuel mass fractions greater than 0.17 result in explosions with a distinct fire ball out of the door. These three regimes accurately describe the results of all tests except tests SBD58 and SBD64 for which there were deflagrations in the spaces even though the fuel mass fraction was 0.14. The reasons for these two outliers is unknown. A detailed analysis of

these tests has shown that the temperature and species concentration measurements are in good agreement with similar tests (SBD47 and SBD49) that did not produce any deflagration.

Table 16. Comparison of Water Spray Injection Backdraft Tests with Respect to Fuel Mass Fraction

Y_f	Y_f before water injection	Test	Volume of Water		Outcome of Backdraft Test
			(L)	(gal)	
0.14	0.24	BD93	13.7	3.6	No flame, no fire ball
0.14	0.24	BD95	13.7	3.6	No flame, no fire ball
0.14	0.25	BD102	13.7	3.6	No flame, no fire ball
0.14	0.19	SBD47	8.9	2.4	No flame, no fire ball
0.14	0.19	SBD58	8.5	2.2	Small fire ball
0.14	0.20	SBD64	9.8	2.6	Roll out of flame under soffit
0.15	0.19	SBD49	5.9	1.6	No flame, no fire ball
0.15	0.24	BD96	10.9	2.9	No flame, no fire ball
0.16	0.25	BD114	10.9	2.9	Very weak pressure pulse, roll out of flame
0.16	0.25	BD92	13.7	3.6	Very slight pulse, long ignition delay
0.16	0.22	BD90	10.9	2.9	Small fire ball (4 m extension from compartment)
0.16	0.25	BD89	10.9	2.9	Small fire ball
0.17	0.25	BD98	8.2	2.2	Small fire ball
0.17	0.25	BD99	8.2	2.2	Small fire ball
0.19	0.25	BD100	5.5	1.5	Fire ball (larger than BD98 and BD99)

Overall, the test results indicate that the use of water spray suppresses a Class B explosion primarily by means of diluting the atmosphere and reducing the fuel mass fraction rather than by a thermal mechanism of cooling. Further evidence for this conclusion can be found in the flammability diagram of Fig. 31 which has been reprinted here for convenience. The initial gas mixture (without water) in the fire compartment can be represented by point D. The fuel concentration is greater than the critical fuel mass fraction; therefore, as air is introduced into the fire compartment (line D-A), an explosive mixture will be created. Due to the high temperatures in the fire space (>300°C), it is reasonable to assume that all water injected is turned to steam; thus, it can be treated as an inert gas. For the purpose of illustration, the steam can be treated as though it were nitrogen (i.e., the right axis could be any inert gas). The injection of water into the compartment is equivalent to moving down the right axis from point D toward point B. Any mixture which is below point C (i.e., the critical fuel fraction) will not result in an explosion as air mixes with the fuel-rich fire compartment gases (e.g., line B-A).

The cooling effect of water spray injection can be seen in Fig. 33. This Figure shows two plots of the vertically averaged temperatures within the fire space for a test with and a test without water injection. The upper and lower plots represent the temperatures measured at locations 3-16-2 and 3-17-1, respectively, for tests SBD46 and SBD47. There is very good agreement between the temperature profiles of both tests. The rapid rise in the temperature at about 1250 s for the test without water is a result of the backdraft explosion. As noted on the Figure, this thermal spike occurs after the door is opened. The test with water injection did not result in a backdraft explosion as evidenced by the absence of a temperature rise after the door was opened. The data illustrate the minor thermal affect water injection had on the fire space. There is less than a 10°C temperature difference before the door was opened between the test with and the test without water injection, (i.e., the temperature at the times denoted with arrows in Fig. 33). As can be seen in Fig. 33 for the test with water injection, the temperature in the fire space decreased relatively quickly during the time of water injection from 1205s to 1265s. However, within the 60s between securing the water injection and opening the fire door, the average temperature increased about 40°C, such that it was equivalent to the average temperature in the fire space for the similar test without water injection. Therefore, these tests show that there was a minimal gas cooling effect due to the water injection. As a matter of fact, the bulkhead temperature measurements for the tests shown in Fig. 33 indicate equivalent or even slightly higher temperatures for the test with water addition.

The result that water injection caused a minimal thermal effect is further illustrated in Table 17 which shows the average fire compartment temperature for similar tests with and without water injection for tests in which water prevented a backdraft explosion. The temperatures presented represent a 10 second average of both thermocouple trees within the fire space prior to the fire door being opened. In general, the temperature decreased about 35°C due to water addition. Of more importance is the fact that even with water injection, the fire space temperatures were typically greater than 300°C. The autoignition temperature for diesel fuel can be taken to be about 250°C since the temperature for similar fuels, JP5 and kerosene, are reported as 242 and 255°C, respectively. Therefore, all the tests with water injection had average compartment temperatures greater than the autoignition temperature (AIT) for the fuel. The fact that all tests had temperatures greater than the AIT and only tests with fuel mass fractions of 0.15 or less resulted in no explosion, indicate that the use of water injection suppresses a Class B explosion primarily by means of diluting the atmosphere and reducing the fuel mass fraction rather than by cooling the space. This conclusion may seem counter-intuitive to many fire fighters who have been taught to fight a fire by knocking down the overhead temperature with a water spray. However, the discussion pertains to preventing explosions, not fire fighting. In fighting a fire, it is advantageous to reduce the overhead gas temperature in order to reduce radiant feedback to the fuel source. This tactic will aid in controlling and extinguishing the fire. In general, a greater reduction in the gas temperature will lead to greater control of the fire via minimizing its size. With respect to explosion prevention in these tests, the gas temperature represents an on/off switch which either allows a backdraft to occur if the gas temperature is above the AIT or inhibits the backdraft if the gas temperature is below the AIT.

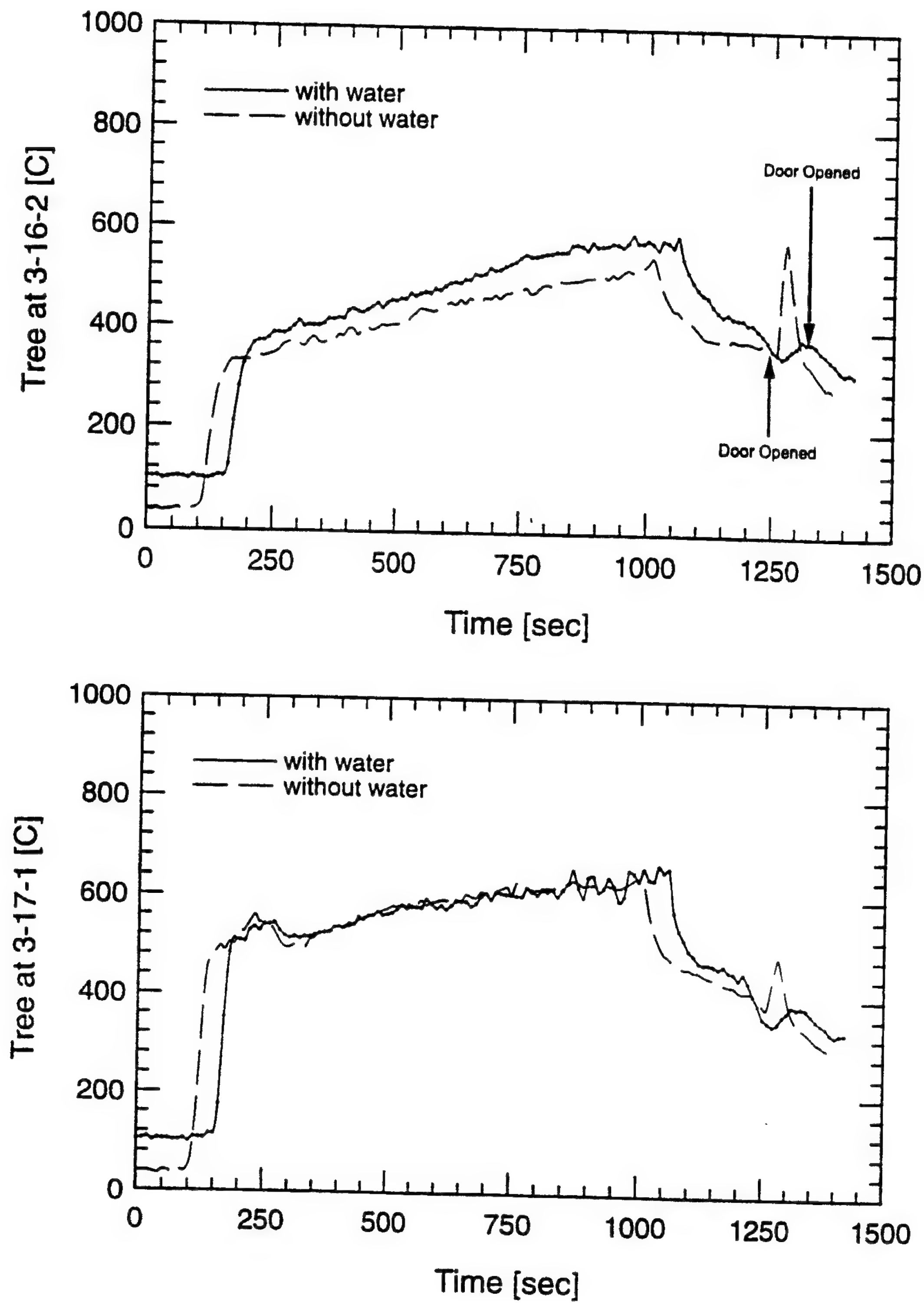

Fig. 33 - Comparison of averaged temperature profiles for backdraft tests with and without water injection (SBD47 and SBD46, respectively).

Table 17. Comparison of Average Fire Compartment Gas Temperatures for Similar Tests with and without Water Injection for Tests in which Water Prevented a Backdraft

Test without Water		Test with Water		Temperature Change due to Water
Test	Temperature (°C)	Test	Temperature (°C)	
BD94	348	BD93	276	72
BD97	346	BD95	311	35
BD97	346	BD96	310	36
BD101	373	BD102	329	44
SBD46	389	SBD47	383	6
SBD46	389	SBD49	356	33

8.0 SUMMARY AND CONCLUSIONS

The use of Class B fuels aboard Naval ships presents unique challenges when accidental leaks and/or fires develop. As opposed to Class A materials, Class B fuels tend to volatilize more quickly resulting in either rapidly growing fires or the build up of fuel vapors within the space. The primary Class B hazard is the case in which the fire has extinguished, and fuel continues to vaporize and fill the space. This situation can lead to a dangerous reflash or a backdraft explosion when air flows into the fire space, such as during reentry. The extended time delay in ignition, sudden formation, and the magnitude (energy content) of the explosion make the backdraft condition extremely dangerous.

The current Navy doctrine provides little specific guidance on reentry of abandoned, out-of-control fire spaces and overhaul procedures. This is despite the acknowledgment that the reentry procedure is potentially the most dangerous procedure. The lack of specific fire fighting tactics was the motivation for conducting the 1995 Class B Firefighting Doctrine and Tactics Program.

The Series 1 tests conducted onboard the ex-USS SHADWELL highlighted the conditions and hazards associated with Class B fires. Under burning conditions, the fires produced high levels of toxic gases, high temperatures, and even the transport of flammable gases. Of greater concern was the susceptibility of Class B fires to extinguish and quickly create explosive mixtures. After Series 1, goals of the program were adjusted to investigate the development of Class B explosions and possible tactics that could be used to mitigate the explosion potential of fire compartments that have been secured. This report presented the work performed in Series 2 through 5 conducted at the Naval Research Laboratory Chesapeake Beach Detachment and onboard the ex-USS SHADWELL.

Overall, the objective for Test Series 2 to 5 was to obtain a scientific understanding of the development and mitigation of Class B explosions aboard Naval ships. This consisted of three main points: (1) determining the conditions needed for developing a Class B explosion, (2) determining the effect of shipboard conditions (e.g., buffer zone size and ventilation) on the development of Class B explosions, and (3) determining the effectiveness of using water spray as a mitigating tactic.

In general, the test series were successful in

1. Establishing a safe and reproducible Class B fire test scenario which resulted in an explosion (backdraft),

2. Demonstrating that active desmoking can safely improve tenability of the buffer zone for Class B fires,

3. Showing that securing ventilation and closing boundaries had no mitigating effect on the Class B explosions for buffer zone to fire space volume ratios of 0.57 or higher,

4. Showing that decreasing the size of the buffer zone increased the intensity of a Class B explosion originating from within the fire space,

5. Showing that securing buffer zone boundaries increased the intensity of a Class B explosion originating from within the fire space,

6. Showing that explosion intensity is more dependant on buffer zone boundary conditions rather than buffer zone ventilation,

7. Revealing that fuel mass fractions of 0.16 or higher are needed for the creation of Class B (No. 2 diesel fuel) explosions in highly vitiated environments (less than 2 percent oxygen),

8. Demonstrating that water injection can be used as a mitigating tactic to suppress a Class B explosion or hazardous reflash, and

9. Demonstrating that the use of water spray suppresses a Class B explosion primarily by means of diluting the atmosphere and reducing the fuel mass fraction rather than by a thermal mechanism of cooling.

9.0 RECOMMENDATIONS

This study of Class B fires aboard Naval ships has identified several key parameters necessary to develop a hazardous Class B explosion, most importantly the fuel mass fraction. It has also been shown that the critical fuel mass fraction (i.e., the minimum fuel concentration that can produce an explosion when mixed with air) is dependent on the oxygen concentration of the fire environment. Based on these results, further work should continue toward developing instrumentation that can accurately measure the critical fuel mass fraction and the oxygen concentration. These measurements would provide firefighters the information needed to make a pivotal assessment of the potential hazard of reentering or incorrectly ventilating a fire space.

The program has also shown that buffer zones of Class B fires can be safely ventilated to improve conditions for firefighters. Ventilation should follow desmoking procedures as outlined in NSTM 555 for Class A fires. Ultimately, instrumentation should be used to assess whether the environment is flammable. However, at the current time, such instrumentation does not exist that can function accurately in smoke filled environments. If fuel aerosol is present as indicated by a white mist/smoke, the gases should be vented only if ignition along the ventilation path is not probable. In general, it is deemed safer to ventilate a space as soon as possible to prevent the build up of a flammable mixture of fuel vapors rather than secure the space which can potentially create a fuel-rich environment. Further study is recommended to assess the

effectiveness of ventilating not just the buffer zone but the fire space. Particularly for main machinery spaces, the fire zone can be vented directly to weather. This procedure should be combined with water spray injection into the fire space. The water spray will serve two purposes. As demonstrated in this test program, water spray can be used to mitigate the explosion potential. In addition, the creation of steam can be used as a driving mechanism to vent fuel-rich gases to weather. Otherwise, to successfully ventilate a fire space, make-up air is required. However, introducing air into the space is the hazardous procedure which is trying to be avoided.

The recommendation to ventilate the fire space is not intended to preclude the current "buttoning-up" procedure for out-of-control Class B fires. However, it is considered to be a more specific fire fighting tactic for reentering and overhauling the fire space than that stated in NSTM 555. Toward this end, specific reentry tactics need to be defined and tested. Based on the success of the water spray injection technique, it is recommended that the effectiveness of an installed water wall, as used by the British Navy, be investigated. The water-wall tactic consists of establishing a sheet of water across a hatch or door via fixed flat spray nozzles. It is expected that this tactic in combination with spraying water into the space will provide adequate protection to fire fighters by suppressing or mitigating explosions and dangerous reflashes. Alternate tactics may include the use of smoke curtains at the access to the fire space. However, this may not always be practical due to geometry and space limitations.

As part of the study to investigate appropriate ventilation and reentry tactics, the size and location of the vent to the fire space should be considered. The backdraft work by Fleischmann indicated that the manner in which a space is ventilated impacts the probability of creating an explosive condition. It is uncertain whether the mitigating effect observed by Fleischmann with the use of a window style vent compared to a long slot is due to a reduction in size or due to the different geometry. The two main issues are the entrainment and the mixing processes of the fuel-rich gases and air. These issues can be examined experimentally and/or numerically with the use of computational fluid dynamics codes.

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